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PREPARED BY WSH

CHECKED BY EPC

NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF MECHANICAL ENGINEERING

OTTAWA, CANADA

LABORATORY MEMORANDUM

SECTION Engine Laboratory

No. NRC-ENG-83

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COPY NO. 23

DATE May 1974

SECURITY CLASSIFICATION.....

SUBJECT The Case for a Diesel-Electric Hybrid Vehicle

PREPARED BY W.S. Heggie

ISSUED TO Internal

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MECHANICAL ENGINEERING
LABORATORY MEMORANDUM

NO. NRC-ENG-83

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1.0 Introduction

A considerable amount of work and consideration has been given, by the writer, to the problems associated with improving the overall efficiency of propulsion in road transportation vehicles. The contents are therefore not entirely the result of accelerated research due to the present fuel situation. The fact that the finite reserve of conventional fuels has invaded public awareness, may provide an environment which is more amenable to some re-orientation of convenience in the area of transportation.

There are three main reasons for the poor economy of the bus and automobile:

- (a) The prime mover rarely runs at the load for optimum SFC.
- (b) In urban driving, as much as 25% of the shaft horsepower is absorbed by inertia and dissipated in brake heat and engine braking friction.
- (c) The gasoline engine may under reasonably optimized conditions, be operated with a BSFC of some 0.55 lb/bhp/H. However, the diesel similarly treated may be expected to consume 0.35 lbs/bhp/H over a wider range of speeds and loads.

2.0 Hybrid Spark Ignition

Reference to figure one shows that a 2500 lb. vehicle will cruise on the level, with no wind, at 50 MPH with an input of 15 BHP, while 65 BHP is required at 50 MPH to accelerate at 6 feet/sec². While all of this power is necessary for top-end acceleration, very attractive lapsed time speeds are possible with constant power and electrical transmission (Fig. 1A).

The foregoing performance is obtainable from a conventional vehicle. Even with expensive manual transmissions and overdrive units, however, the level-road SFC probably averages 0.75 lb/bhp/H. (Ref. Fig. 2).

As a result, the highway performance of the conventional compact car may average some 35 MPG, with a speed pattern comprising approximately 25% between 40 and 50 mph, 50% between 50 and 60 mph and 25% between 60 and 70 mph.

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If energy storage is provided for acceleration and hill climbing, optimum engine size and operating parameters for highway cruise speed may be chosen (see Fig. 2) with a resulting fuel consumption of some 0.55 lbs/bhp/H, or $\frac{35 \times .75}{.55} = 47.8$ plus 3% for removal of gearbox = 49.2 MPG on the highway with straight through drive. However with electrical losses for moderate amounts of town driving 45 MPG is a practical figure.

Regenerative braking (See Fig. 3) advantages are self-evident but it is less generally appreciated that some 10% may be recovered as a result of grade and speed change on highway driving, resulting in a consumption equal to 49.5 MPG. Reduction in highway load results in engine pumping and mechanical friction losses. Viz. Cyclic acceleration in road speed % is assumed to occur at the following rate per hour:- 25% x 2, 10% x 10 and 5% x 60. This is deemed to represent approximately 10% x 60 or accelerating 60 times per hour to 6.5 MPH. Based on subject parameters and $W = \frac{w}{2G} V^2 \times 60 = 480,000$ ft. lbs. representing .1865 lb. SFC and $\frac{.1865}{.8} \times 100 = 23.3\%$. As this low energy cycling is ideal from the regenerative point of view, 45% recovery is thought feasible, hence the 10% claimed above.

3.0 Hybrid Diesel

Large turbo-charged diesels operate with fuel consumptions as low as 0.33 lb/bhp/H and (Fig. 4A) small machines may be optimized in the region of 0.36 or slightly better at some expense of specific power. There are, however, some small machines with SFC as low as 0.34 (Fig. 4B).

Optimized for power, the small medium speed diesel has a power to weight ratio of about 7 lbs. per bhp and about 10 if optimized for fuel economy. A 15 HP engine therefore may weigh from 105 to 150 lbs. If the difference is treated with a scaling down factor of 25% it becomes 56 lbs. As a ratio of the vehicle under consideration, this represents 2.2%, half of which may be considered a direct sacrifice in fuel, in terms of MPG. The latter is approximately proportional to weight/2 under highway conditions at about 50 MPH. This leaves a net gain of 8.9% with diesel.

This factor is considered reasonable, particularly in view of the probable necessity of using a 3 cylinder engine at somewhat lower RPM, in which case the electric motor may not provide adequate WR^2 , necessitating a larger flywheel.

The diesel-electric arrangement in the subject vehicle may therefore accomplish a fuel consumption of $49.5 \times .55 = 75.6$.

.36-

Fuel consumptions from 40 to 120 MPG, with car weights from 4,000 (touring) to 1,300 lbs. (runabouts) are evidently feasible (Fig. 5).

4.0 Choice of Concept

Many attempts have been made at producing hybrid powerplants, with varying success. Diesel-inertia has had the inherent problems associated with torque conversion to and from the flywheel and when electrical methods are used, double losses have to be tolerated; kinetic losses continue even when no flywheel energy is being converted.

Springs, hydraulics and gas compressing systems are subject to problems of equal magnitude to that of the flywheel system.

The battery even in its present state of development, presents few problems; applied to the hybrid system, where storage is only required to cope with acceleration and regeneration, surprisingly small battery weights and capacities are required.

Figure 1A shows that 50 HP in a parallel hybrid system may accelerate a 2500 lb. vehicle to 50 MPH in 12 secs. with an acceleration capability at that speed of some $3'/\text{sec}^2$ (one in ten grade). 50 HP minus 15 diesel horsepower is assumed to be the electrical requirement and an additional short duration 15 HP for emergencies. 35 HP for 10 seconds x 10 accelerations to 1/2 battery life is therefore the normal rating and requires only $\frac{35 \times 746 \times 10 \times 10 \times 2}{60 \times 60} = 1450$

watt hours, or less than 3 x 50 amp. hr. batteries weighing some 168 lbs. However, maximum discharge rates are some four times rated capacity $\therefore \frac{746 \times 35}{50 \times 4 \times 12} = 10$ batteries weighing some 550 lbs.

Higher voltages are recommended in practice to permit more efficient circuit and motor design, thus reducing I^2R losses and reducing motor and generator costs, and in the final analysis performance may be traded to some extent for battery weight.

5.0 Conclusions

1. It is assumed as a point of departure that a conventional compact car of 2500 lb. is capable of cruising at 50-60 mph with a consumption of 35 mpg.

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2. A gasoline-electric hybrid engine, sized to the 50 mph road load could achieve a consumption of 52 mpg.

3. A diesel-electric hybrid for the same weight vehicle and operating conditions could achieve a consumption of 73 mpg.

4. The weight of a 4-passenger diesel-electric vehicle would be expected to exceed that of the compact conventional vehicle by 500 lbs. viz. the small diesel should equal the larger petrol engine and weight saved due to less fuel stored and gearbox removal should approximate electric motor weight. A 2100 lb. compact should therefore provide a 2700 lb. hybrid.

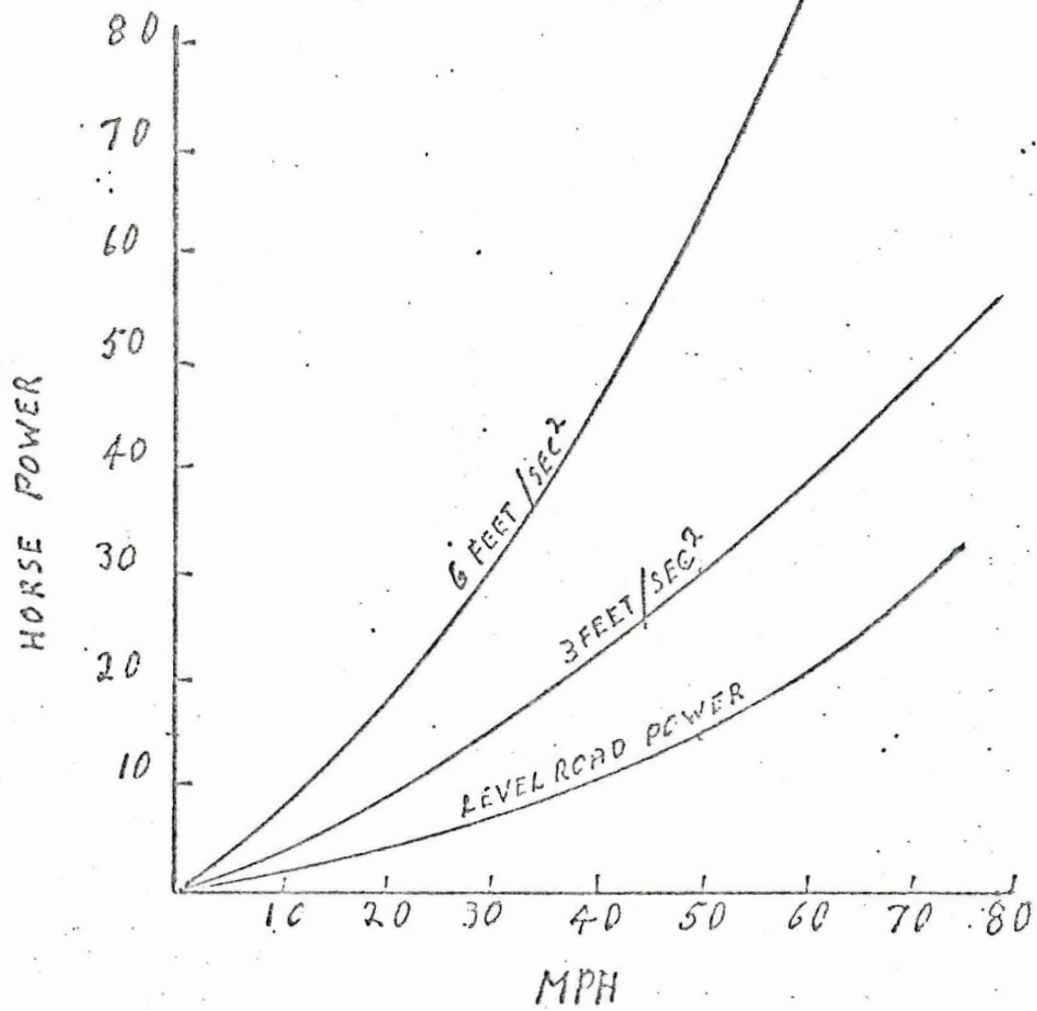
6.0 Appendices

1. Specifications

Battery capacity 1/2 life in watt hrs.	2,500
Battery 10 second per minute discharge rate in watts	37,000
Engine BHP	15
Vehicle Weight	2,700

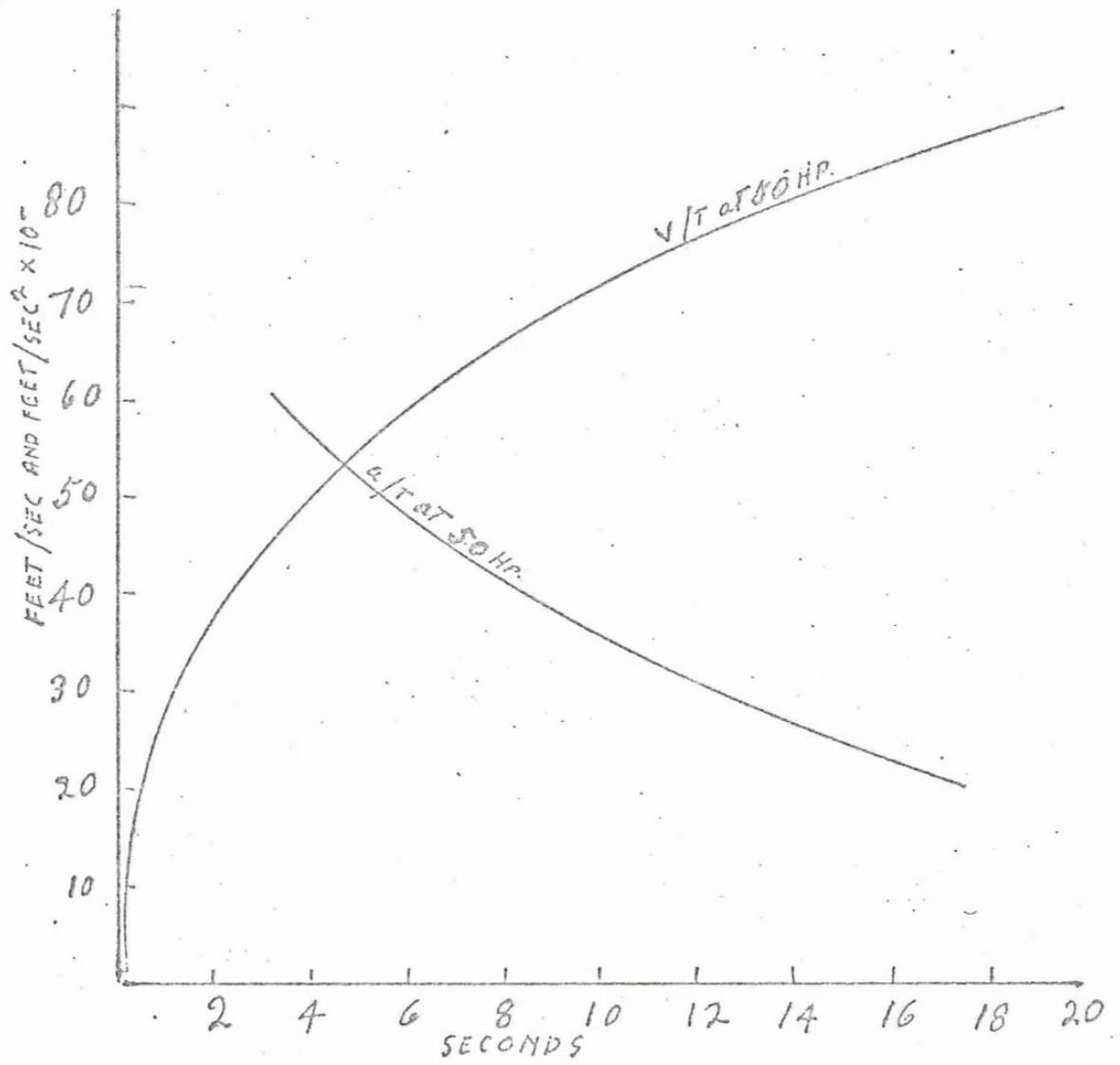
2. Performance

Cruise speed	60 MPH
Max. speed 1 mile bursts	80 MPH
Acceleration av.	6 ft/sec ²
Emergency range on batteries only at 35 mph	50 mi
Immediate power available at 0°F from cold start	30 HP
Normal operating temp. obtained in	3 mins.



POWER & ACCELERATION FOR A 2500 LB. CAR.

FIG 1



CONSTANT HORSEPOWER CHARACTERISTICS OF A 2500 LB CAR.

FIG 1A

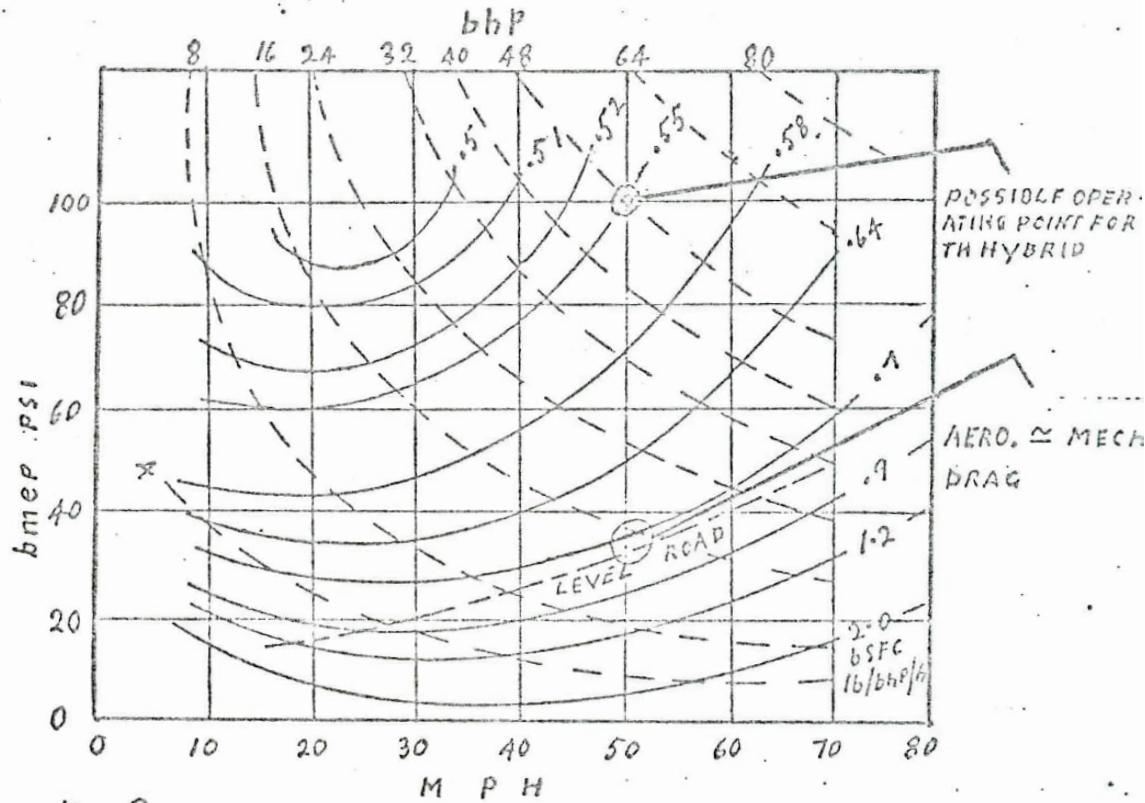
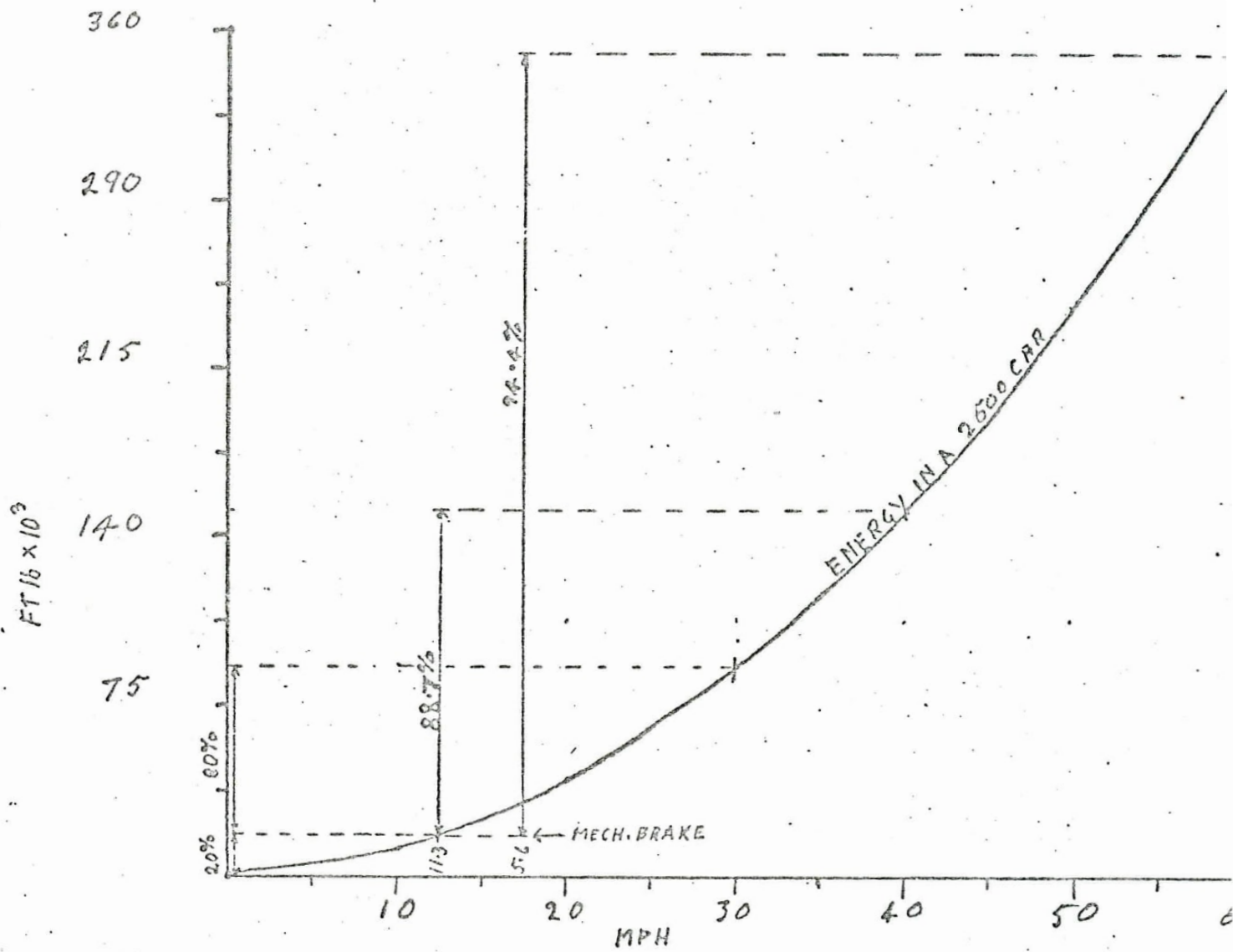
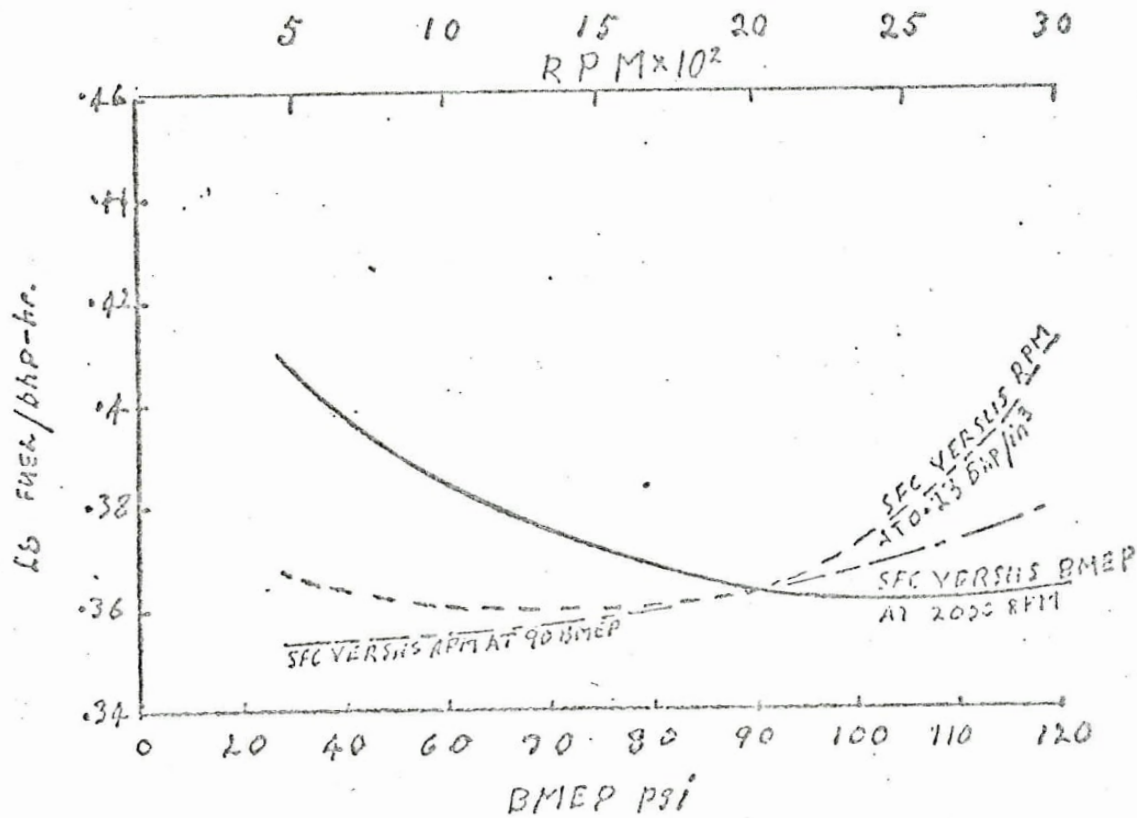


Fig 2 PERFORMANCE MAP 2,500 LB CAR

AN EXTRAPOLATION BASED ON DATA FROM TAYLOR'S
 "THE INTERNAL COMBUSTION ENGINE"

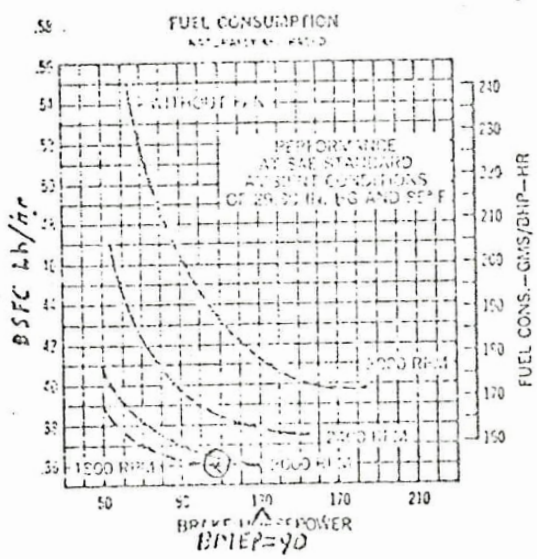


AVAILABILITY OF ENERGY FROM REGENERATIVE BRAKING
 2500 LB CAR
 Fig 3



COMPILED FROM HIGH SPEED DIESEL DATA WITH SQUARE BS RATIOS APPROXIMATING 4" (CONSTANT TEMP. AND TIMING ETC.)

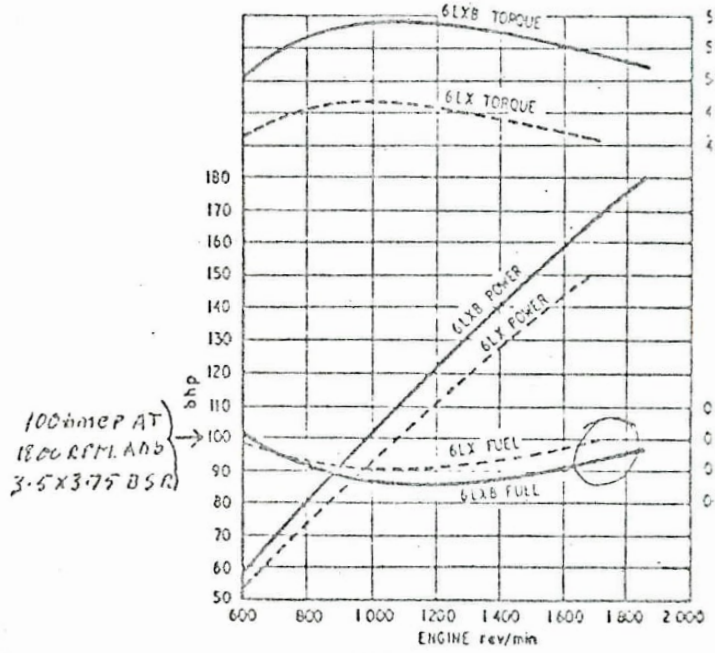
FIG 4



EXAMPLE OF DATA USED FOR ABOVE

FIG 4A

FROM CATERPILLAR DIESEL GUIDE



Comparative full-load performance curves of Gardner 6LX and 6LXB 10-45 L engines

FIG 4B

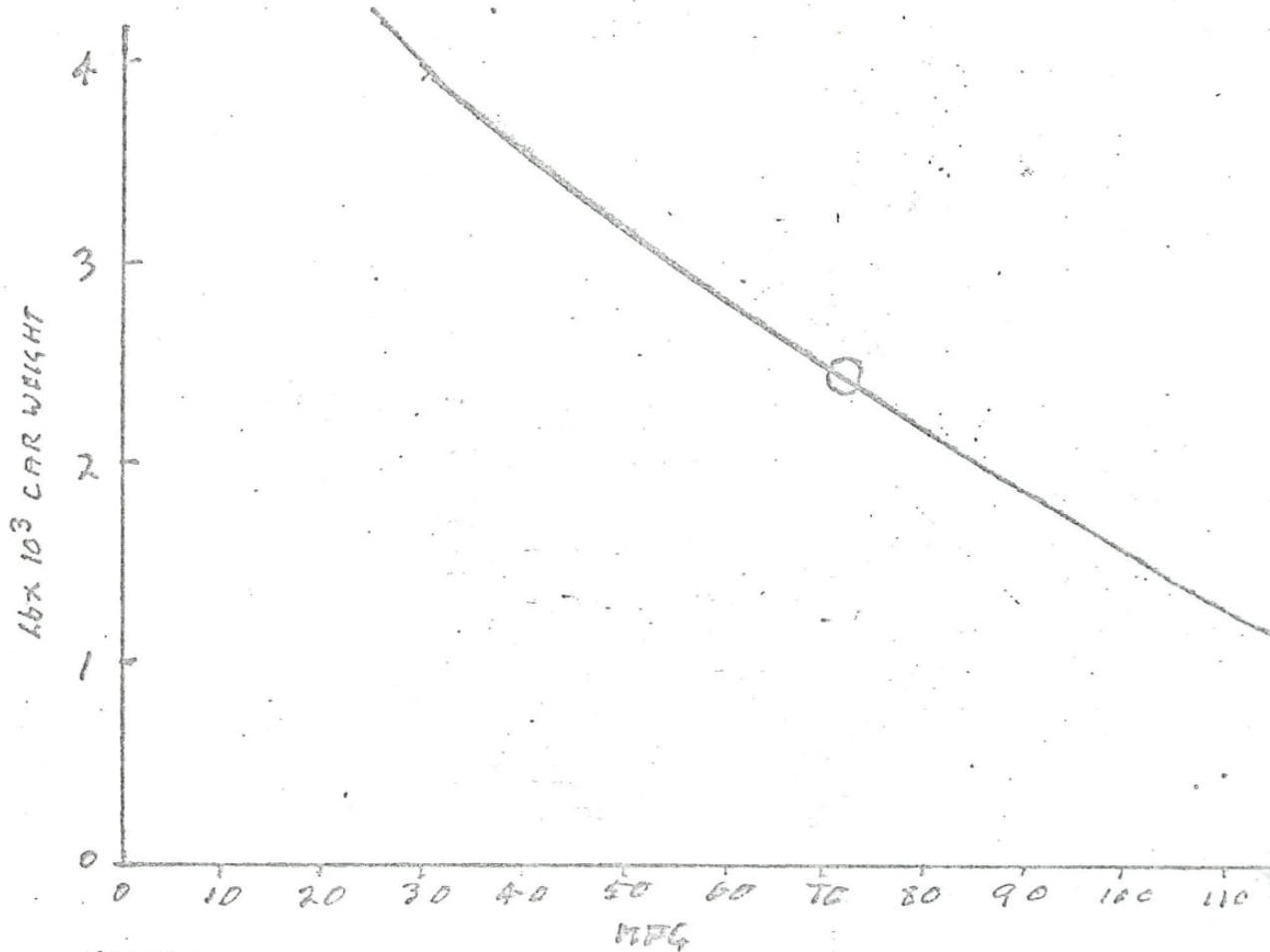


FIG 5 CAR FUEL CONSUMPTION AT 50 MPH WITH OPTIMISED CONSTANT LOAD SPEED DIRECT DRIVE DIESEL

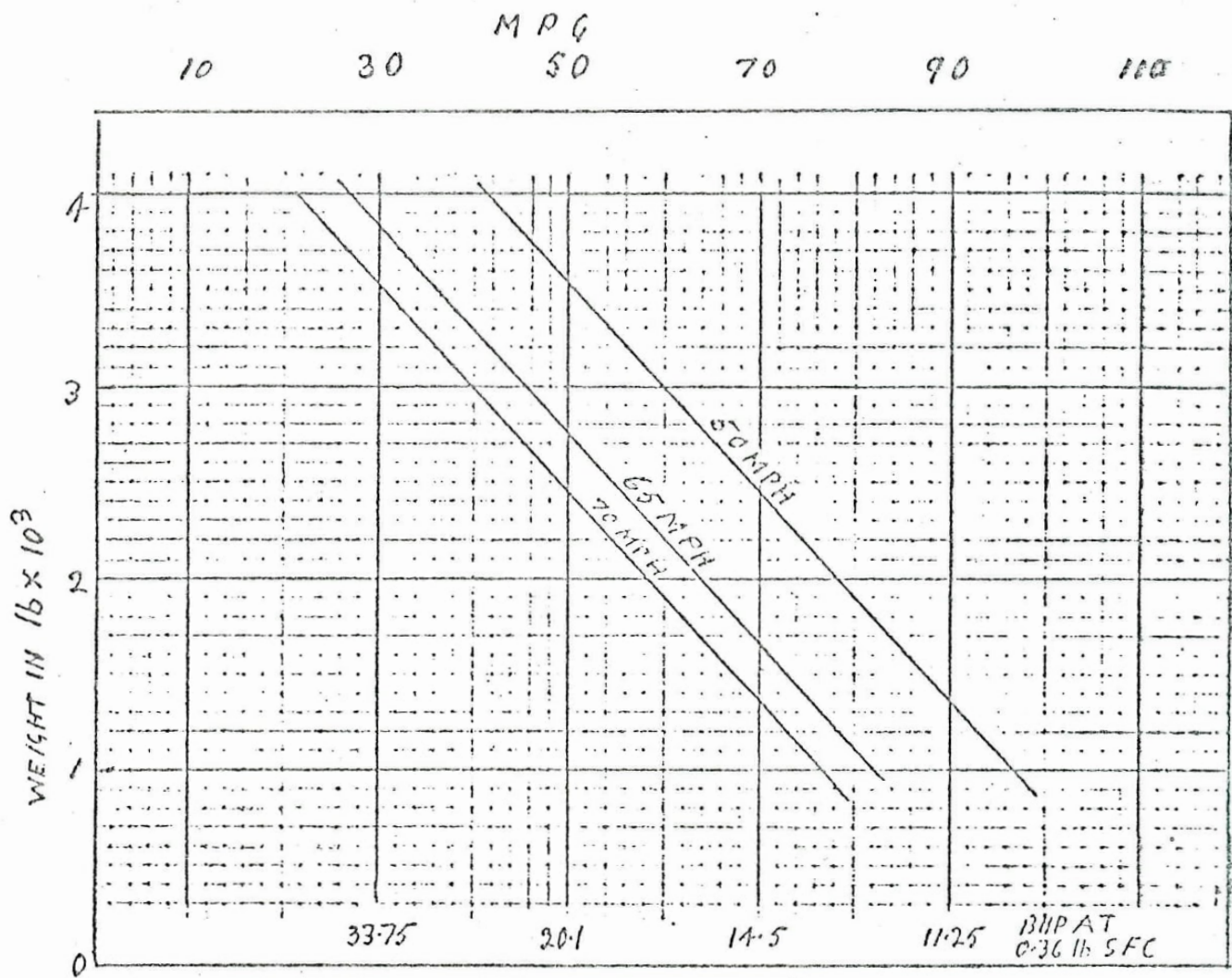


FIG 5A CAR FUEL CONSUMPTION - CONSTANT LOAD DIESEL