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Fuel economy goals for future powertrain and engine options

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Abstract: Efficiency goals represent one of the key factors governing powertrain choice. These goals are specified for three novel developments in automotive technology which would enable them to compete on this single basis with the conventional four-speed manual or automatic transmission (with torque converter lock-up) coupled with a fixed displacement spark-ignition engine. The fuel consumption figures of continuously variable ratio and infinitely variable ratio automobile transmissions are presented using a simulation model of a vehicle in both urban (EPA cycle) and constant-speed operation. A powertrain utilising a variable displacement engine is also simulated.

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1 Introduction

Several powertrain options currently exist for future automobiles which offer variable gear ratios and engine capacities (Amann, 1986).

Numerous designs of continuously variable ratio transmissions (CVT), and variable displacement reciprocating internal combustion engines (VDE) have been proposed, and some have been taken to the stage of mass production. Whilst each design has its own advantages and disadvantages, there is a requirement to review the specifications that are necessary for such new equipment to enable them to compete successfully with conventional manual and automatic gearboxes, as well as fixed displacement reciprocating internal combustion engines. The goals are often a moving target because methods have been made available as a result of recent research and development to improve the performance of current powertrains without changing the basic design concept. The performance indices must include fuel consumption, driveability, exhaust emissions, reliability, as well as initial and operating costs.

This paper directs attention to one of these major performance goals — vehicle fuel consumption calculated over a road cycle and at constant speed.

It is intended that these results should, in isolation, give an indication of the desired fuel economy goals to be achieved before the novel powertrains are likely to be considered as competitors.

Whilst fuel economy does not rate as the most important performance index in the 1980s, it will inevitably play a major role in the longer-term development of the personal automobile. Finite petroleum reserves and the predicted 'greenhouse' effect are two factors which should discourage complacency.

2 Automotive powertrain developments

The continuously variable transmission concept has been studied by numerous authors (Mitschke, 1981; Stubbs, 1981; Stieg and Worley, 1982; Yang and Frank, 1985). In addition, the efficiency of manual and automatic powertrains has been examined by Van Dongen (1982). The infinitely variable transmission (IVT) is a CVT with an unlimited gear ratio range, i.e. the engine can be operating and torque produced on stationary wheels, with an effective gear reduction of infinity. One successful prototype of such a transmission using a split-path electromechanical arrangement was reported by Gilmore and Bullock (1982).

Many automobiles are still produced with manual transmission and most are now four-speed. The four-speed automatic with lock-up of the torque converter in every gear is established in the market-place and represents commercially viable technology. The efficiency in each gear will then closely approach that of a manual transmission.

Reciprocating internal combustion engines of fixed displacement dominate the automotive market-place. Variable displacement engines utilising a variable stroke capability have been proposed since the 1890s and recently investigated by Siegla and Siewert (1978) and Scalzo (1986). Such designs could be regarded as competitors to continuously variable transmissions, as they are also able to increase the brake thermal efficiency of the powertrain at partial load and at any road speed. The CVT does this by allowing continuous selection of a gear ratio between engine and road wheels which will optimise the engine efficency, normally at a relatively low engine speed, and high torque.

The variable displacement engine is able to de-stroke on partial load, thereby creating a fractional size displacement and a higher efficiency at a given torque and speed. The fully stroked engine is still available for peak acceleration and hill climbing capabilities.

3 Scope of investigation

This paper gives the results of calculations performed to evaluate the fuel consumption of a standard vehicle when operated with a variety of powertrains over two types of driving styles.

3.1 Road power losses

Post *et al.* (1983) report that the Australian fleet averaged vehicle has a mass of 1160 kg, and that the total drag power (kW) absorbed by the vehicle can be represented by equation (1):

$$Z_{\text{total}} = Z_{\text{drag}} + MV(a/3.6 + 9.81\sin\theta)/3600 \tag{1}$$

$$Z_{\text{drag}} = (0.036V + 0.45\times 10^{3}V^{2} + 0.8\times 10^{-6}V^{3} \tag{2}$$

where M is the vehicle's mass (kilograms), V is the vehicle's velocity (km/h), a is the vehicle's acceleration (km/h/s), θ is the road gradient (degrees), and Z is the drag power (kw).

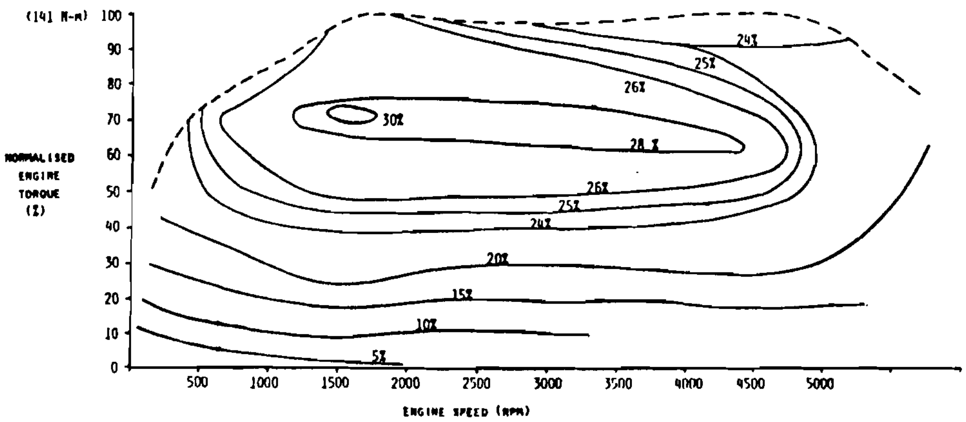
This specification is typical of the average vehicle produced for the worldwide automobile market.

3.2 *Internal combustion engine*

A nominal 2-litre reciprocating spark-ignition engine was chosen as the typical power plant for the purposes of this analysis. This size is also representative of the power plant which is commonly installed in a 1160 kg vehicle. The total brake thermal efficiency contours of such an engine were measured, and are depicted in Figure 1.

Figure 1 2-litre spark-ignition engine brake thermal efficiency contours as measured

Gross Calorific Value of Fuel 47.2 MJ/kg



3.3 *Manual transmission*

The baseline fuel consumption was calculated for a manual transmission with the gear and differential ratios listed in Table 1.

Variations in ratios for a range of vehicles have been accounted for by calculating the variation in fuel consumption which would arise from a ± 10% variation in the differential, and therefore the overall, transmission gear ratio.

Limited data available on the efficiency of manual transmissions (Van Dongen, 1982) suggests that the overall mechanical efficiency in any gear at greater than 20% of rated torque will be 95% (tolerance +0%, −2%) at the operating temperature. All transmissions will suffer a drop in mechanical efficiency at part load, whether they are manual, CVT or IVT. To avoid another variable in this analysis, the mechanical efficiency of a manual transmission in any gear at any load was fixed at 95%.

Similarly, the efficiency of a final-drive differential has been taken at 97%, based on the data given by Van Dongen (1982) and this author's research.

TABLE 1 Ratios for manual gearbox

Gear	1	2	3	4	Differential
Ratio	3.71	2.16	1.37	1.0	3.73

3.4 *Infinitely variable transmission (IVT)*

An infinitely variable transmission (IVT) attached to the 2-litre engine was simulated. This transmission could adjust to any speed ratio between the input and output shafts that suited the operation of the engine for maximisation of efficiency.

The ratio could be anywhere between ± infinity:1. The part load efficiency characteristics of such transmissions will depend on their design. The intention of this paper is to evaluate the worth of different gearbox ratio options rather than their individual efficiency characteristics. However, the overall average efficiency of such a transmission is very important, and so an 'average' efficiency has been adopted. Calculations have been performed for average efficiency of the IVT's of between 70% and 95%. It is argued that it is most unlikely that an IVT would achieve an average greater than that of a manual transmission.

3.5 *Continuously variable transmission*

The CVT adopted in this paper is an IVT with a restricted overall speed ratio. The maximum ratio allowed in the CVT in these calculations is 3.71:1 (equal to the 1st gear ratio in the manual transmission) and the minimum ratio is 0.742. This gives an overall speed ratio range of 5:1. Predictions of the likely consequences of increasing this speed ratio range can be gained from interpolation of the CVT and IVT results. Slip and losses in the clutch which will be necessary between the engine and the CVT are both assumed to be negligible.

3.6 *Variable displacement engine (VDE)*

The variable displacement engine modelled in this paper is able to destroke from a capacity of 2 litres down to 1 litre. This 2:1 ratio appears to be representative of likely future developments in this technology. The engine is attached to a manual gearbox of similar specification to that described in Section 3.3.

Such an engine would most probably be attached to an advanced automatic gearbox with lockup in each gear, and the transmission is therefore well modelled by the manual gearbox for the purposes of this paper.

3.7 *Urban driving cycle*

The Australian design rule 27C (1982) for vehicle emission control specifies the 1372 second duration EPA (USA) urban driving schedule for test purposes. This cycle has been used for an evaluation of fuel consumption in stop–go urban conditions at speeds between 0 and 92 km/h.

Post *et al.* (1981; 1983), have derived a fuel consumption matrix for the ADR 27C cycle. Each matrix cell entry represents the number of one-second observations that a vehicle is within the boundaries of a particular acceleration and velocity cell, when it is driven over that cycle on a dynamometer. Their work extended to mapping other road cycles in a similar manner, based on measurements from instrumentation attached to vehicles as they were driven on the road. They reported that the instantaneous power demand model which considered a complete driving cycle to be a series of short trip cells at the specific cell velocity and acceleration, was able to predict the aggregate fuel consumption of a vehicle to an accuracy better than 2% of that determined volumetrically on the road or dynamometer.

This model has been used to calculate the urban drive cycle fuel consumption by calculating the engine torque and speed necessary to achieve the velocity and acceleration in each cell, with each of the transmission options and their control logic. Fuel consumption is determined by evaluating the efficiency of the engine at that torque and speed from Figure 1. The total engine power required is given by equation (1) with the grade angle θ set to zero. At some negative levels of acceleration, it is possible that Z_{total} is zero. In that case the engine will be operating in a high-speed idle condition, and the fuel consumption rate is obtained by linear regression of experimental data on the engine type selected.

Normal idle in the drive cycle at zero velocity, zero acceleration is accounted for by a 212 second cell entry at a velocity of 2.5 km/h. Each cell entry encompasses a 2.5 km/h speed range and a ± 0.5 km/h/s acceleration range. Fuel ccnsumption as measured at specified idle speed was 3.36×10^{-4} litres/s. This idle consumption was also assumed for conditions demanding a negative total engine power (retardation).

3.8 Constant speed operation

Whilst the majority of automobiles consume fuel in conditions represented by the many urban drive cycles available, constant speed operation provides information at the opposite extreme and is more indicative of freeway or open highway driving.

4 Powertrain control strategy

Each powertrain considered requires a control logic to govern its operation.

4.1 Manual transmission

At any particular velocity and acceleration the software attempts to operate the gearbox in its highest gear (4th). This would produce the highest possible torque and lowest speed operation which is the general criteria accepted for economical driving. The driver, however, will override this requirement if the resultant engine speed is below what he regards as an acceptable minimum, depending greatly on the engine design, its mounting construction, and the presence of unwanted resonances. Commonly, this is about 1300 prm, but recent designs allow minimum engine speeds well below 1000 rpm. Generally, the fuel supply systems are not designed for extra-low speeds, but operation down to 600 rpm at full throttle might be considered by manufacturers in the near future.

The strategy for gearbox operation was to operate in the highest gear possible, whilst ensuring that engine speed did not fall below a set minimum. The engine torque was also prohibited from rising above 126.9 N m (70% of the maximum engine torque of 141 N m) which is the torque producing the generally highest efficiency of the engine. Efficiency falls at higher torques which are reserved for peak power demands. Most manufacturers recommend a change to a lower gear (higher gear ratio) as correct driving practice, and this procedure was adopted in these control algorithms.

4.2 *Infinitely variable transmission (IVT)*

Attempts are made to maintain torque at an optimum level for maximum engine efficiency through the use of the IVT. A level of 126.9 N m (70% of maximum torque) is maintained up to a speed of 2500 rpm. Engine speed is calculated to provide the power required by the driving cycle. Should the speed fall below the set minimum chosen, that set speed is selected by the software and the torque recalculated to a level below the optimum. Should the engine need to exceed 2500 rpm the torque will be set at a level given by equation (4).

$$T = (70 - 0.004B\,(N - 2500))\ 1.41\ \text{N m} \tag{4}$$

One iteration is performed to calculate the engine speed as follows. Torque is set at 126.9 N m and engine speed N is calculated to provide the power required by the driving cycle. If N is greater than 2500 rpm, T is calculated using equation (4), and N subsequently recalculated. If N exceeds a practical limit of 5000 rpm, that speed is selected and the torque is recalculated to a level above the optimum.

The maximum gearbox ratio achieved is calculated but not restricted in any way.

4.3 *Continuously variable transmission (CVT)*

The control of the CVT is identical to the IVT except that the gearbox ratio between engine and driveshaft speeds is restricted as discussed in Section 3.5. If the software of the IVT demands a ratio greater than 3.71 or less than 0.742, then the ratio is fixed at those limits, and the engine torque re-calculated.

4.4 *Variable displacement engine (VDE)*

The control software for the transmission follows that of the manual gearbox to select initially an appropriately high gear (low ratio). If the torque required, based on the 2-litre engine, is below the optimum torque specified for IVT operation (Section 4.2), the engine is destroked in an attempt to locate a smaller engine capacity which will have that torque as optimum, assuming that the normalised shape of the efficiency contours does not alter. At the upper and lower limits of engine displacement, the capacity is fixed at either 1 litre or 2 litres, and the appropriate overall efficiency calculated.

As the average efficiency of a VDE will undoubtedly be somewhat less than that of a fixed displacement engine because of compromises necessary in the combustion chamber surface/volume ratio, location of spark plugs, and the mechanism used to alter the stroke, calculations have been performed in this paper with relative mechanical efficiencies between 70% and 100%, compared with a fixed displacement engine.

4.5 *Range of modelling for aggregate fuel consumption*

Each powertrain has been modelled over the urban drive cycle with specified minimum engine operating speeds of between 600 and 2000 rpm as an input variable.

Constant speed operation has been modelled between 10 and 160 km/h. For these latter calculations, the minimum engine speed was set at 1300 rpm to remove it as a variable.

5 Results achieved

Vehicle aggregate fuel consumption was calculated for each of the powertrain options over the urban driving cycle and at constant speed. Results are given in Figures 2 to 15.

Figures 2 to 5 depict the dependency on both the minimum engine speed desired and the differential ratio over the urban drive cycle. The IVT and CVT are specified as having a mechanical efficiency of 95%, whilst the VDE has an efficiency of 95% relative to the manual powertrain. Essentially, lower differential ratios yield lower fuel consumption, as would be expected, except for the IVT which is able to optimise the engine efficiency independently of the drivetrain gear ratios. The manual powertrain fuel consumption can vary by ±3% at minimum engine speeds below 1000 rpm, whereas at 1300 rpm minimum there is no advantage in selecting a differential ratio below 3.73:1.

The IVT is able to produce a 6–12% reduction in fuel consumption compared with the manual (MAN) transmission (Figure 3). The 12% reduction occurs at a minimum engine speed of 1800 rpm. The CVT and IVT are essentially identical with minimum speeds between 1000 rpm and 1600. Above 1600 rpm, the CVT uses approximately 3% less fuel as the restricted ratio enforces lower engine speeds than the desired minimum and higher engine efficiencies (Figure 4). Below 1000 rpm, the IVT uses up to 4% less fuel than the CVT as it is able to take advantage of these extra low speeds over the total driving cycle.

At a relative efficiency level of 95%, the VDE with manual transmission (Figure 5) achieves between 13% and 24% lower fuel consumption than the MAN powertrain. This result is largely independent of minimum engine speed, up to approximately 1400 rpm.

Figures 6 to 8 depict the dependency on both the minimum engine speed desired and the relative efficiency of the powertrain over the urban drive cycle with a differential ratio of 3.73:1. Figure 6 shows that the mechanical efficiency of the IVT can fall to an average of 70% before fuel consumption equals that of the MAN drivetrain. However, the MAN powertrain fuel consumption can be lowered by reducing the differential ratio whereas

Figure 2 Fuel consumption ADR27C city cycle: manual transmission

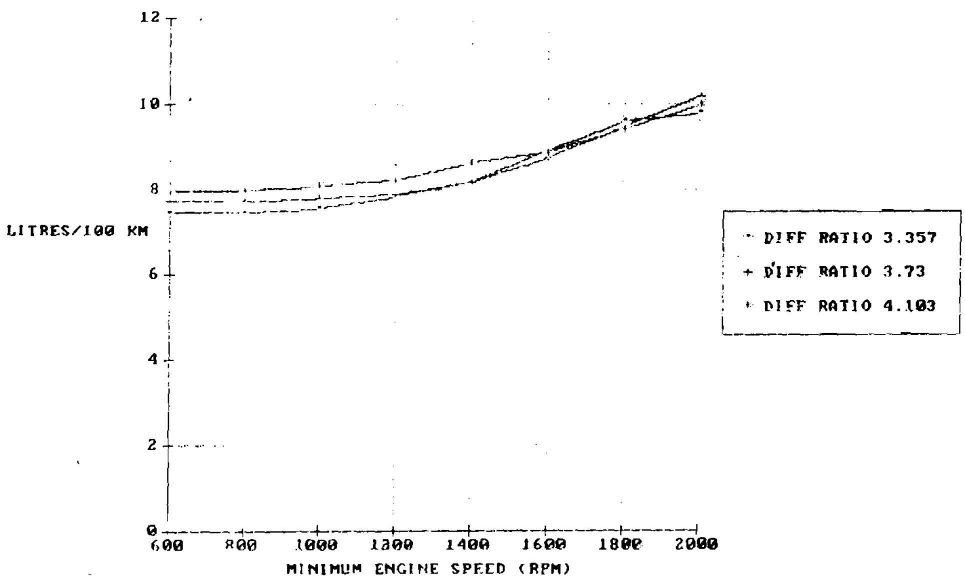


Figure 3 Fuel consumption ADR27C city cycle: unrestricted cut ratio with efficiency of gearbox 95%

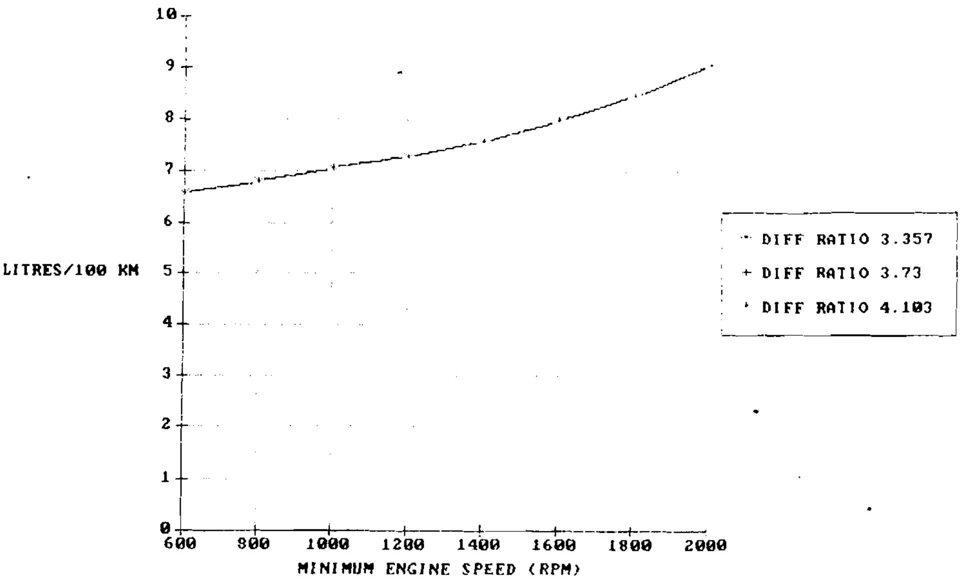
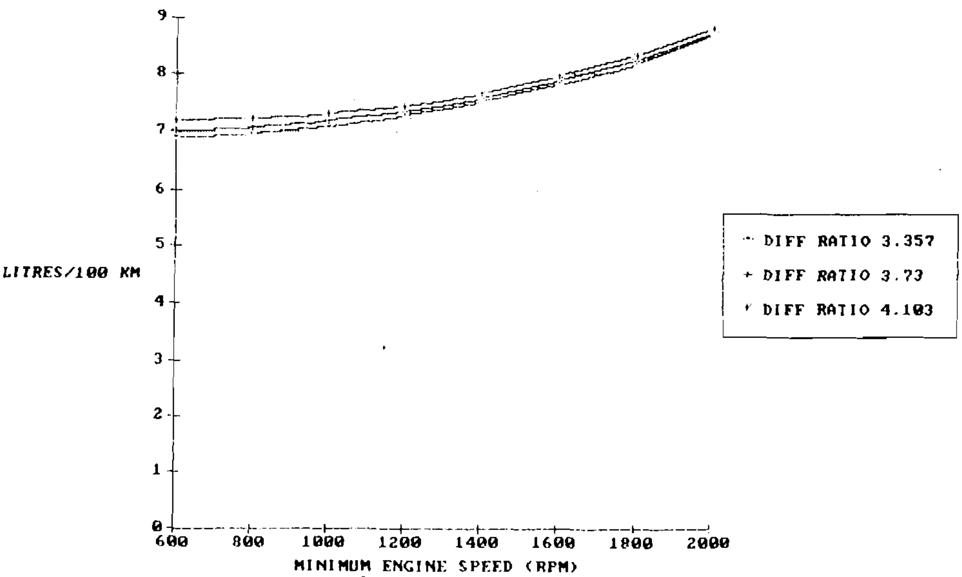


Figure 4 Fuel consumption ADR27C city cycle: restricted ratio cut 3.71:1 with gearbox efficiency 95%



it has no effect on the IVT. Therefore, the mechanical efficiency of the IVT can only fall to an average of 82% before fuel consumption equals that of the MAN powertrain with a differential ratio of 3.357:1 and a minimum engine speed of between 1000 and 1300 rpm.

Figure 7 shows that the CVT must also achieve an average of 82% mechanical efficiency to equal the best performance of the MAN powertrain, and at least 80% to equal the performance at a differential ratio of 3.73:1.

Figure 5 Fuel consumption ADR27C city cycle: variable displacement engine, efficiency 95%

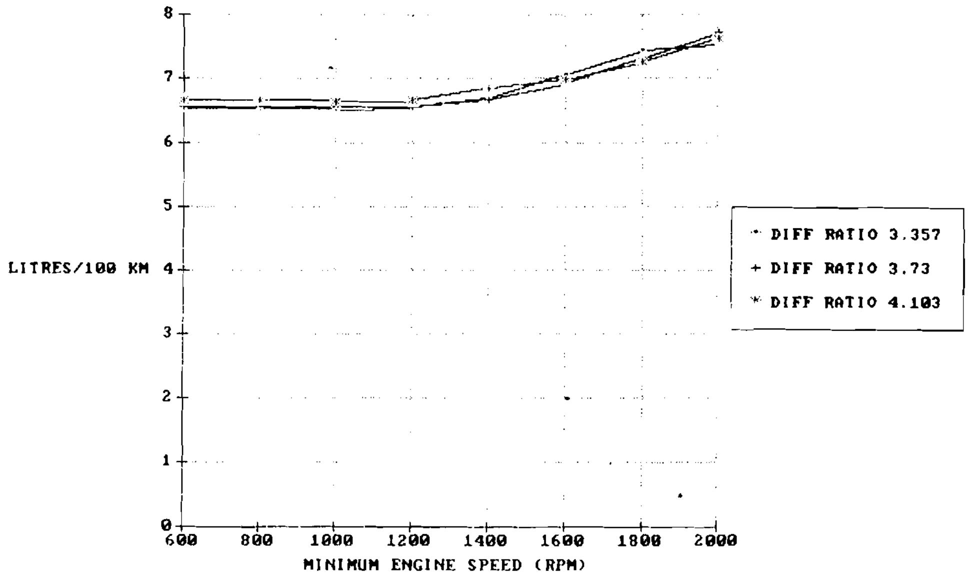
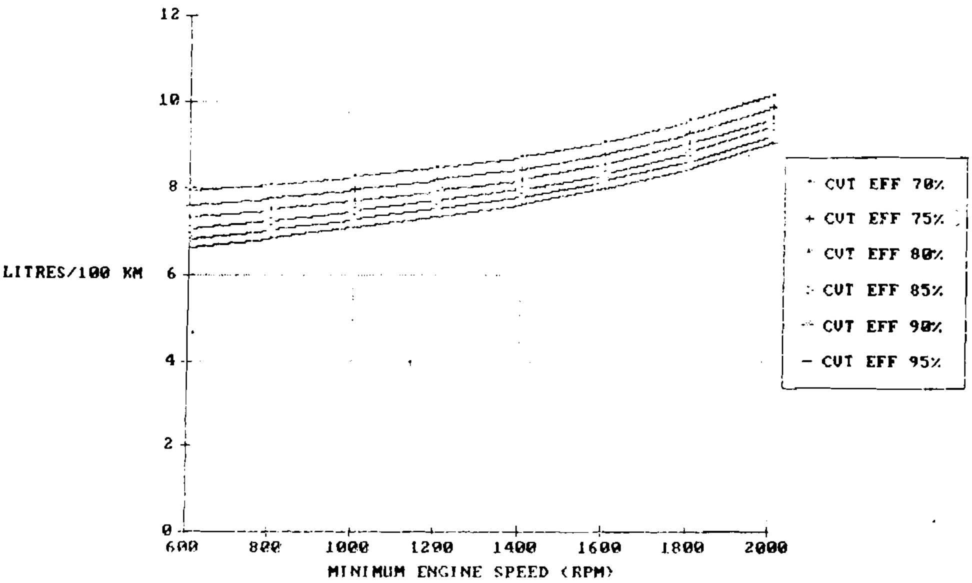


Figure 6 Fuel consumption ADR27C city cycle: unrestricted cut ratio, differential ratio = 3.73:1



The VDE data of Figure 8 shows that it must achieve an average efficiency of at least 75% relative to the fixed displacement engine to allow it to equal the performance of the MAN powertrain with a differential ratio of 3.73:1 or 80% with a differential ratio of 3.357:1 and minimum engine speeds below 1000 rpm.

Figures 9 to 12 depict for all powertrains the dependency of fuel consumption on constant driving speed and differential ratio. Again the IVT and CVT are specified as having

Figure 7 Fuel consumption ADR27C city cycle: restricted ratio 3.71:1 cut, differential ratio = 3.73:1

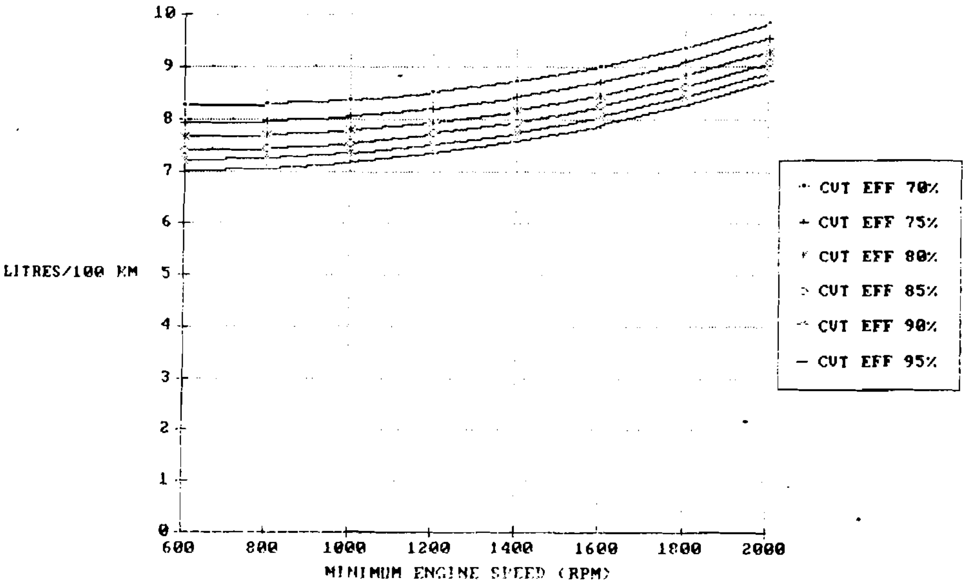
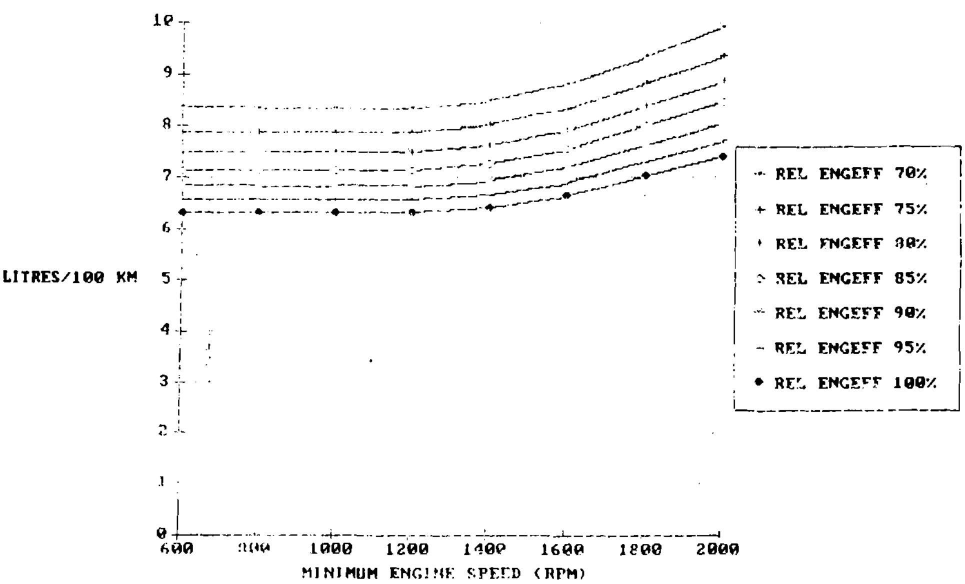


Figure 8 Fuel consumption ADR27C city cycle: variable displacement engine, differential ratio = 3.73:1



a mechanical efficiency of 95% whilst the VDE has an efficiency of 95% relative to the manual powertrain. Minimum desired engine speed was set at 1300 rpm in all powertrains.

The MAN powertrain achieves minimum fuel consumption at between 40 and 60 km/h with variations of $\pm 12\%$ depending on the differential ratio.

As anticipated, the IVT fuel consumption (Figure 10) is not dependent on differential ratio and has a broad low consumption region of less than 6 litres/100 km between 40

Figure 9 Fuel consumption at constant speed: manual transmission

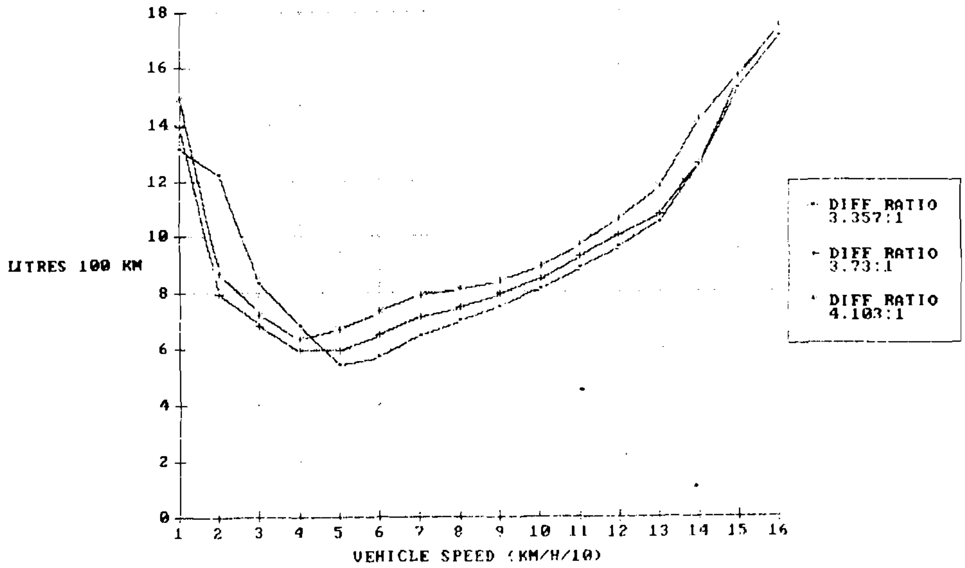
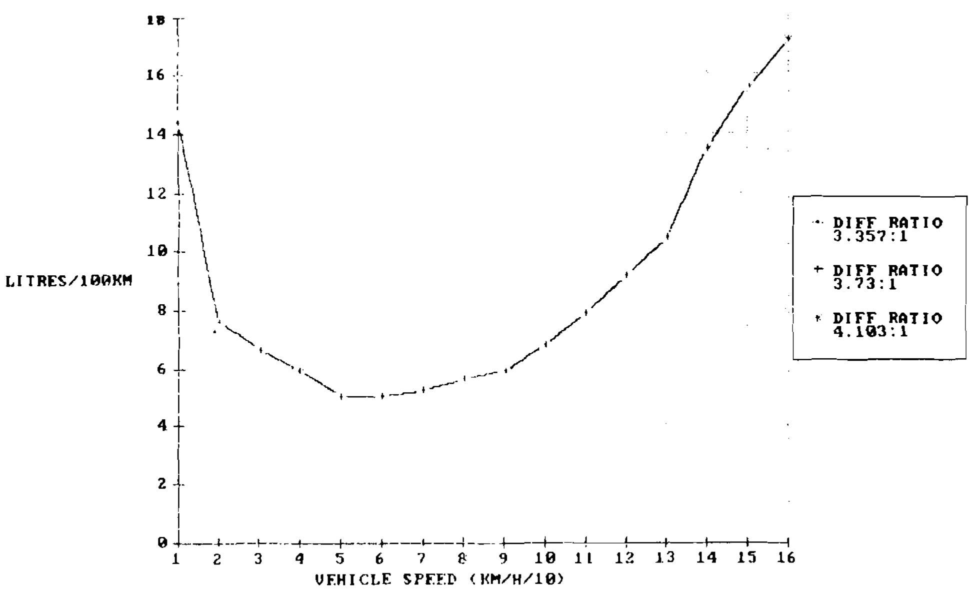


Figure 10 Fuel consumption at constant speed: unlimited ratio cut



and 90 km/h. In that region, fuel consumption is between 10 and 20% lower than that for the MAN powertrain with a 3.357:1 ratio. This reduction is a little more than that found with the urban drive cycle. The CVT result of Figure 11 shows that the fuel consumption is as low as that of the IVT between 50–60 km/h, but 8% higher at 100 km/h. Dependency on the differential ratio is generally small and negligible below 50 km/h, and above 120 km/h.

Figure 11 Fuel consumption at constant speed: restricted ratio 3.71:1 cut

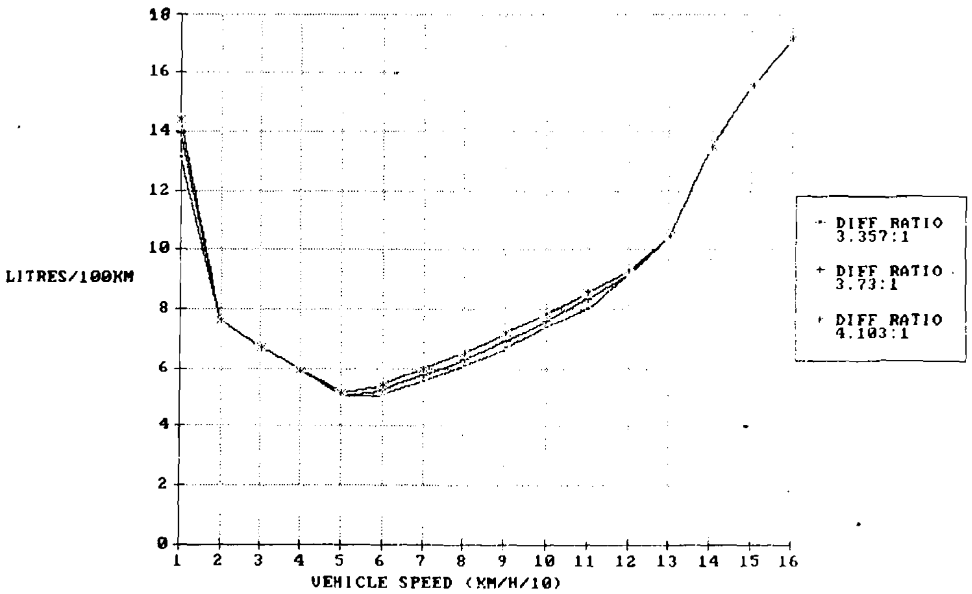


Figure 12 Fuel consumption at constant speed: variable displacement engine, efficiency = 95%

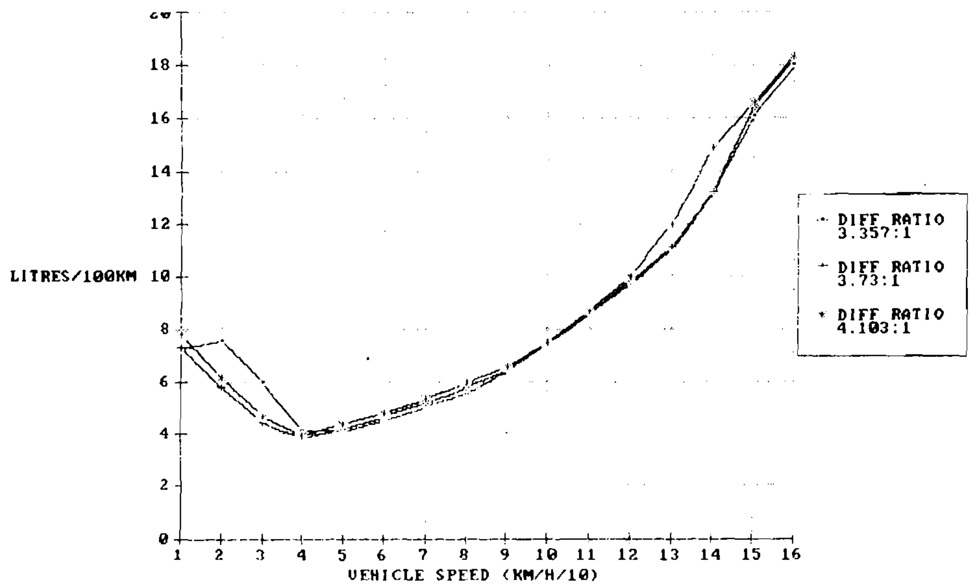


Figure 12 shows that the VDE has a broad 20 to 85 km/h speed band where fuel consumption is less than 6 litres/100 km. The VDE uses 33% less fuel than the MAN drivetrain at 40 km/h, 25% less at 50 km/h, and the same at 120 km/h. At speeds greater than 120 km/h the drag power requirement would demand the 2-litre displacement engine, which has been specified as having a 95% relative efficiency compared with the 2-litre fixed displacement engine. Hence, the fuel consumption of the VDE fuel below that of the MAN powertrain.

Figure 13 Fuel consumption at constant speed: unlimited ratio cut

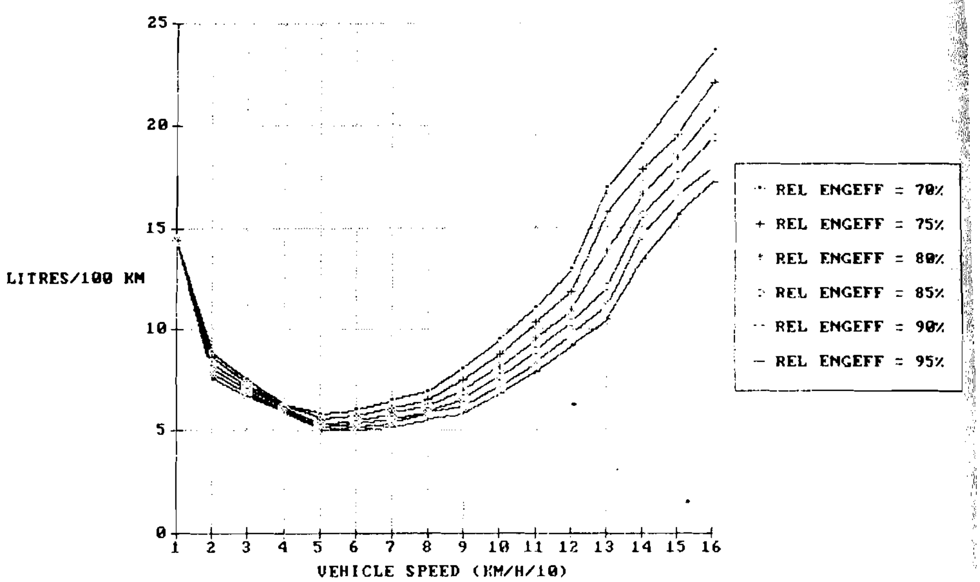
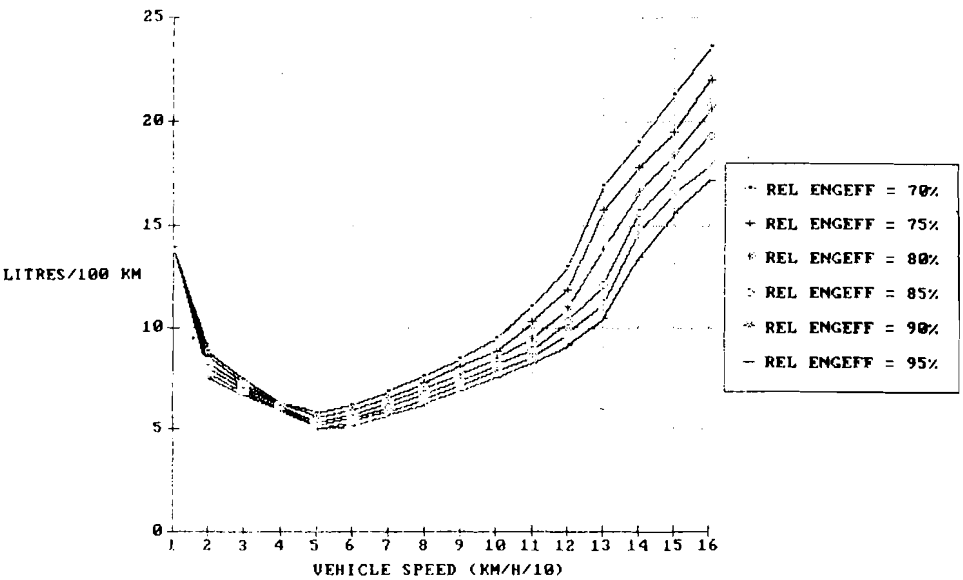


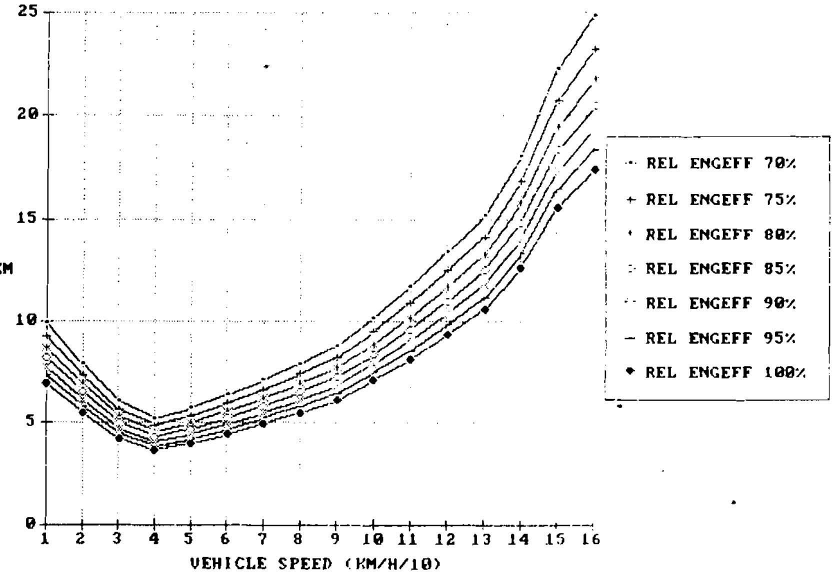
Figure 14 Fuel consumption at constant speed: restricted ratio 3.71:1 cut



Figures 13 to 15 depict for the IVT, CVT and VDE, the constant speed fuel consumption dependency on relative mechanical efficiency with a differential ratio of 3.73:1. Figure 13 shows that the IVT cannot achieve an efficiency higher than the MAN powertrain (Figure 9) at constant speeds below 40 km/h. At 80 km/h, a relative efficiency of 70% is required, but this rises to 95% at 130 km/h. At higher speeds, the manual transmission is superior.

The CVT (Figure 14) is similar to the IVT below 50 km/h and above 120 km/h. The

Figure 15 Fuel consumption at constant speed: variable displacement engine



relative efficiency to match the MAN powertrain must be higher than the IVT in the intermediate range and typically is 82% at 80 km/h.

Figure 15 depicts that a VDE would require a relative efficiency of less than 70% to achieve the constant speed fuel consumption of the MAN powertrain below 40 km/h; rising to 80% at 80 km/h and greater than 100% at faster than 130 km/h.

6 Conclusions

The following points can be made in summary:

- As a general conclusion fuel consumption is lowered as minimum engine speed with open throttle is reduced, regardless of the transmission design or the type of engine (fixed or variable displacement).

  However, for the three transmissions considered, between 6 and 12% less fuel is consumed with a minimum engine speed of 600 rpm versus 1300 rpm. (If the engine efficiency contours are unchanged).

  The VDE does not however need low engine speed development to achieve fuel savings.

TABLE 2

	Very important	Important	Not important
Manual	•		
IVT			•
CVT		•	
VDE		•	

- The importance of a variation in differential ratio can be summarised in Table 2.
- If an IVT, CVT, or VDE could be made with the same relative efficiency as a conventional fixed displacement internal combustion engine and manual gearbox, then it is clear that major fuel savings would be achieved.

  Typically these will be 6–12% for the IVT, and 6–15% for the CVT.

  The VDE will achieve 13–24% savings.

  However, the following conclusions can be drawn: (i) an IVT or a CVT needs to have > 82% mechanical efficiency on average to be better than a manual gearbox; (ii) a VDE needs to have > 80% relative mechanical efficiency on average to be better than a Manual gearbox with a fixed displacement engine.
- Table 3 summarises average mechanical efficiencies required to achieve benchmark 5% and 10% fuel savings under urban and constant 100 km/h conditions. For the IVT and CVT, lower engine-speed capabilities down to 600 rpm and 800 rpm, respectively, would increase the possible savings.

TABLE 3 Mechanical efficiencies required for benchmark fuel savings

			Average mechanical efficiency (%) required		
Drive cycle	Gain in fuel efficiency (%)	Minimum engine speed(rpm)	IVT	CVT	VDE (relative (efficiency)
Urban	5	1300	90	90	80
Constant 100 km/h	5	—	87	95	93
Urban	10	1300	See (a)	See (b)	85
Constant 100 km/h	10	—	90	See (c)	100

Notes: (a) Impossible: minimum engine speed must be 700 rpm.
(b) Impossible: minimum engine speed must be 1600 rpm.
(c) Impossible.

- If there exists the probability of achieving efficiencies of greater than 90% relative to the fixed displacement engine, on average, then the VDE engine is worthy of further development. There would then be the opportunity to achieve urban drive cycle savings of 15% but no change in the highway cruising fuel consumption at 100 km/h. There is no advantage in reducing the minimum engine speed below 1300 rpm.
- If a 90% average mechanical efficiency can be achieved with the IVT, CVT and VDE, the lowest possible fuel consumption which is indicated by this paper is given in Table 4.

In terms of a fuel economy performance index alone, this paper highlights the development of IVT technology in conjunction with the lowering of the stable operating speed in fixed displacement engines to 600 rpm at high torque levels, as the most fruitful area for further reductions in passenger vehicle fuel consumption.

TABLE 4 Summary of fuel consumption results

Engine type	Fixed displacement (FD)	FD	FD	FD	Variable displacement (VDE)
Gearbox type	Manual	IVT	IVT	CVT	Manual
Gearbox mechanical efficiency	95%	90%	90%	90%	90% (engine)
Minimum engine speed (city) rpm (open throttle)	800	1000	600	600	1300
Differential ratio	3.357	3.73	3.73	3.357	3.73
Fuel consumption urban cycle (litres/100 km)	7.5	7.3	6.8	7.1	6.8
Fuel consumption highway-constant speed 100 km/h. (litres/100 km)	8.0	7.2	7.2	7.8	8.0
Minimum engine speed (highway) rpm	1300	1300	1300	1300	1300

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