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PROBLEMS WITH LEAD/ACID BATTERIES IN AUTOMOTIVE ELECTRICAL SYSTEMS

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Introduction

Modern passenger vehicles show improved performance and reliability in their operation resulting from better technology and well-analysed experience. However, in many vehicles, the battery is being adversely affected. For example, Pacific Dunlop engineers have noticed, with concern, increasing reports of the 'flat battery' syndrome — particularly from automobile service organisations, from reports on cars left at airports, and from analysis of battery warranties. Over 30% of battery replacements in Australia are for 'flat batteries'. Investigations in the U.S.A. report a substantial percentage also (but less than that in Australia).

In Pacific Dunlop's opinion, this situation is a result of several factors:

- in Australia, average journey times are about 30 min, usually in city or urban conditions
- similar short drives at night, particularly in winter
- lighting, heating, and ventilation loads take most of the alternator's output: so when idling at traffic lights, the battery is being discharged; this occurrence is termed 'deficit motoring'
- cold batteries require higher voltages for charging, but alternator temperatures rapidly rise after starting and the regulator turns down the output voltage, resulting in a 'no charge' situation

To investigate this problem, batteries were taken from a considerable number of cars of several makes — batteries which had from 3 to 24 months service — and reserve-capacity tests were conducted without any recharging. The results are shown in Fig. 1, and it can be seen that the bulk of batteries in service are working at about 50% of reserve capacity. The batteries were recharged and retested. As expected, an improvement in reserve capacity was observed, but full recovery was not achieved (due to plate sulphation, etc.).

A further problem that has been encountered is overcharging at high ambient temperatures — this is experienced in many locations. In the case of one very popular Australian car range, alternator temperatures of 110 °C can be experienced on really hot days and 70 °C within 20 min of driving is common. As a result, the manufacturer drastically reduced the nominal set voltage of the regulator — also harshly affecting the battery. At about 60 °C, the lead/acid battery starts to become unstable and continued charging can

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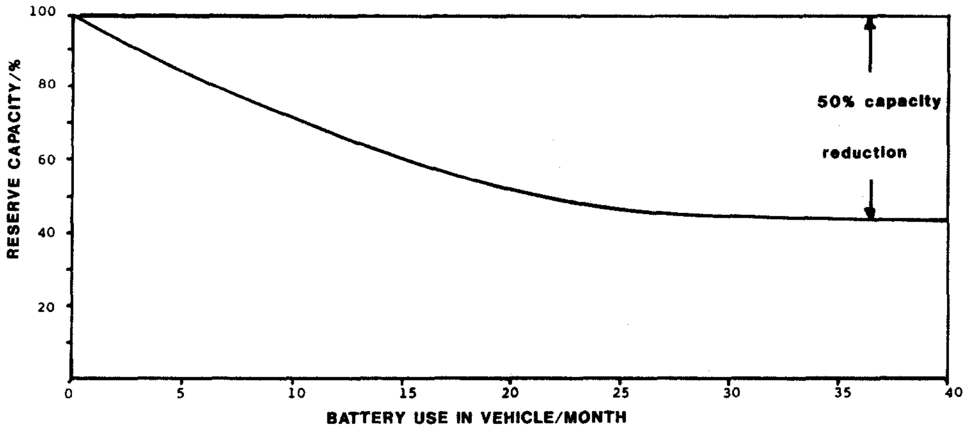

Fig. 1. Reserve capacity *vs.* battery use in vehicle; mean curve for a large sample of batteries.

destroy the battery by excessive electrolyte loss, grid corrosion, or thermal runaway. Consequently, when fitting batteries in vehicles it must be ensured that:

(i) the voltage control given by the regulator does not lead to either overcharging or undercharging;

(ii) the battery is so located that the temperature does not rise above 50 °C.

Temperature considerations are equally important in engine-starting operations. The most difficult engine starts are found to occur when the engine is very hot and the battery is only partly charged. If the battery is fully charged, then engine starts are satisfactory.

Battery technology was previously able to keep up with some of these problems when they were at a lower intensity, *e.g.*, by reduction in the antimony content of the grids and by improvement in the separators. But what has happened to the vehicles? Table 1 summarises recent design changes that are likely to impair battery performance.

A fully-charged battery will always start a serviceable engine but, as seen in Fig. 1, not many batteries enjoy a good state-of-health. In order that the battery be maintained in a fully-charged condition, the electrical system of the vehicle must be able to apply the correct voltage for the temperature at which the battery is operating.

While it is generally agreed that there will be periods of net battery discharge during vehicle operation (*i.e.*, during idling in traffic or from parasitic electrical loads), it is the *degree* of net discharge that is important. Battery manufacturers have a major interest in ensuring that their products are able to work effectively in operating environments. It is of real concern to the manufacturer as to how the battery is used or, perhaps more specifically, abused. To a vehicle owner, a battery that does not work is a bad product, regardless of the reason for its malfunction. Furthermore, automobile

TABLE 1

Battery problems arising from changes to vehicles

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1. Lower frontal-aspect bodies, resulting in reduced airflow through engine compartment.
2. Increased engine-compartment temperatures resulting from:
   - lower cool airflow
   - pollution control equipment
   - catalytic conversion equipment for lead-free petrol
   - turbo charging
   - demand for higher engine performance.
3. Placement of the voltage regulator integral with the alternator.
4. Unsatisfactory design criteria:
   - Poor matching of voltage/temperature characteristics of the voltage regulator and the battery.
   - Incorrect setting of voltage regulator — not high enough to match charge acceptance characteristic of battery used.
   - Mismatch of the alternator and battery — alternator output insufficient to replace energy lost in normal driving cycle.
   - Failure to achieve best location of battery in vehicle.
5. Increased 'key-off' loads on the vehicle electrical system (*e.g.*, 40 mA over 21 days equals 20 A h).
6. Poor control by Original Equipment Manufacturers of electrical systems during both vehicle assembly and in the distribution chain after assembly.

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service associations are very concerned with the battery situation as the majority of call-out service costs are battery related.

Development work at Pacific Dunlop

As a major battery manufacturing company, Pacific Dunlop attaches great importance to the investigation of problems arising from the battery/alternator/regulator relationship. To this end, the Company is conducting an extensive programme of road and laboratory tests. Results have shown that even with 1987 cars, there is insufficient charging taking place to compensate for electrical loads, especially under idling and in wet and dark conditions. It appears that there is no clear appreciation of what is happening to the battery and, in particular, of the requirements for satisfactory in-vehicle charging. The objectives of the Pacific Dunlop programme are given in Table 2.

Voltage regulator/battery relationship

How can a battery be maintained in a fully charged condition in the vehicle? Vehicles are equipped with alternators that must produce the correct voltage when delivering the current demanded by the vehicle's

TABLE 2

Objectives of battery/alternator/regulator studies being undertaken by Pacific Dunlop

1. To balance the vehicle operating system (*i.e.*, battery, alternator, regulator, starter, other electrical loads) so that with *all* electrical loads operating, the alternator output is able to ensure the battery is maintained at over 80% of full charge within the temperature range 0 - 50 °C for the battery and 0 - 95 °C for the alternator.
2. To ensure that the battery can be recharged from 80 - 85% of full charge in an average urban drive time of 30 min with *average* electrical loads and within the temperature ranges given in 1.
3. To ensure that battery temperatures are restricted to 50 °C with only occasional excursions of less than 1 h to 60 °C.
4. To prevent any damaging overcharge conditions to the battery.
5. To ensure adequate voltage levels to other electrical components at low and idle engine speeds.

electrical system, with sufficient excess energy available to recharge the battery at the same time. If this criterion is not met, then perfectly good batteries will run down and fail to start the car. The alternator output is controlled by the voltage regulator which, today, is a solid-state unit that is usually integral with the alternator. However, it is more desirable (from the battery point-of-view) to have the voltage regulator located both separately and close to the battery itself. The main factors affecting charging voltage are listed in Table 3.

Voltage regulators are programmed to provide specified voltages to the battery at 25 °C, together with a given rate of voltage change with temperature. These specified voltages vary between manufacturers. In Australia, voltage settings can be 14.0, 14.2, 14.4, and even 14.7 V; in the U.S.A., a range of 14.4 - 14.8 V is found with Ford vehicles and a range of 14.5 - 15.1 V with General Motors vehicles. In practice, neither batteries nor voltage

TABLE 3

Main factors affecting battery charging voltage

1. Availability of current from the alternator
2. Ability of the charging system to stay out of nett discharge conditions
3. Ambient temperature
4. Age of battery
5. State of original charge
6. Electrolyte level
7. Impurity content of electrolyte
8. Grid alloy specification

regulators remain close to 25 °C during vehicle operation. The temperature of the regulator rises very rapidly after engine starting due to conducted heat from the engine and load on the unit. The battery, having a large mass and a large thermal inertia, changes temperature much more slowly. The latter results in a mismatch of the voltage presented to the battery terminals. This is shown in Fig. 2; the temperature rises apply, typically, to any starting ambient.

Battery voltage requirements for maintaining a fully charged battery with minimum gassing (and therefore minimum water loss) at varying temperatures are given by a thermal correction factor of approximately -20 mV $°C^{-1}$ away from the 25 °C datum. This is shown in Fig. 3(a) and is compared with the voltage/temperature relationship for five various voltage regulators in Fig. 3(b). To control the state-of-charge of the battery fully, the voltage regulator should sense the battery temperature. If the regulator is attached or integral with the alternator, additional feed-back equipment is necessary. Alternatively, the regulator could be made as a separate component (as in older vehicles) and located adjacent to the battery, remote from the alternator. Battery terminal-voltage sensing back to the voltage regulator is now in

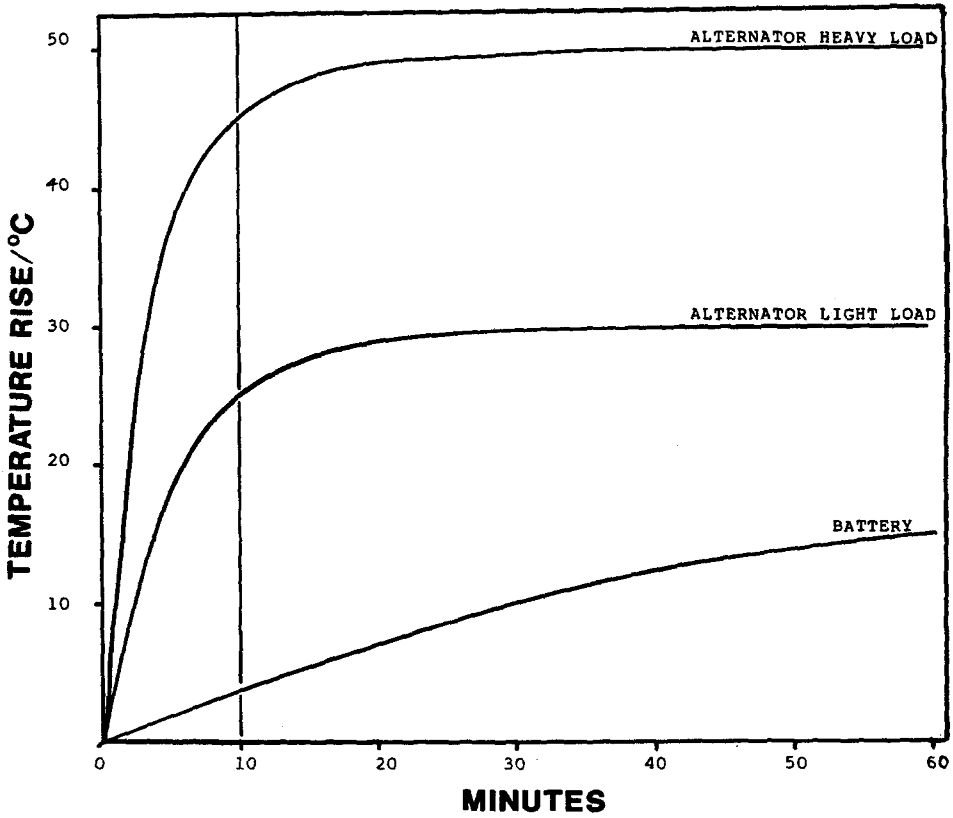


Fig. 2. Alternator and battery temperatures.

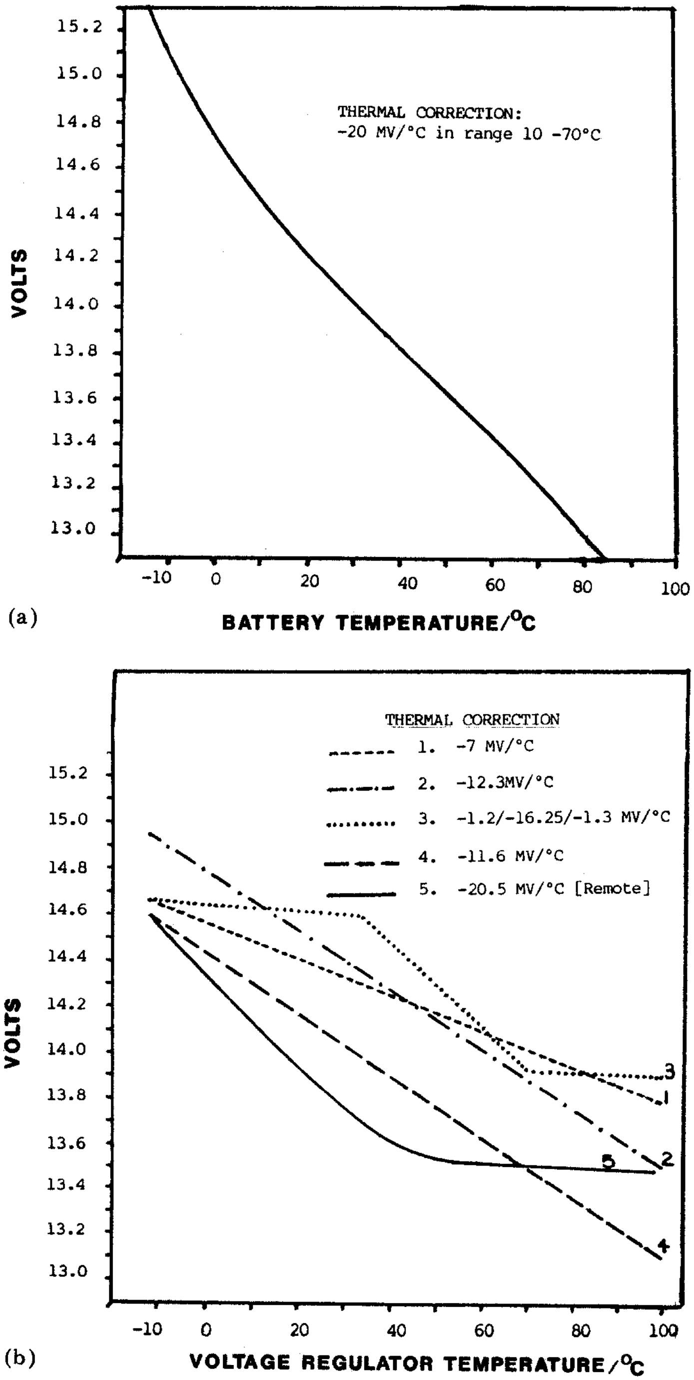


Fig. 3. (a) Voltage required to maintain full charge effectively for a low-maintenance battery at varying temperatures; (b) comparison of present-day voltage regulators with varying thermal correction.

general use and has eliminated voltage losses in the cables. However, it is unfortunate that battery temperature sensing is not being welcomed as yet due to the alleged additional cost. This could be accommodated by reduction in the battery size, provided a properly matched battery/voltage regulator/alternator system is provided.

Situation without temperature compensation

Consider first the present problem *without* the refinement of battery-temperature sensing. The data in Fig. 4 provide a comparison of six different voltage regulators (A - F) with the battery voltage requirement for maintaining full charge. Next, consider the various temperatures encountered in vehicle operation on a cold day followed by those experienced under hot conditions. Analysis is centred on the battery voltage requirement to maintain a typical low-antimony, fully-charged battery in the minimum gassing state (taken as a 100 mA charge current) with the voltage available at the battery terminals from the alternator. Battery-voltage sensing back to the alternator is assumed. Temperature sensing is at the alternator. The voltage/temperature characteristic will vary slightly for different types of batteries, but the slope of the line will remain approximately the same.

Table 4 presents the performance of the six voltage regulators, with differing specific points and characteristics, operating in winter conditions (refer to Figs. 2 and 4). It can be seen that all the regulators provide unsatisfactory cold-weather charging over short driving cycles of 30 min. The problem is that the thermal inertia of the battery keeps it fairly cold in these short time periods, thus giving a high voltage requirement for maintaining a fully charged battery. The voltage regulator, due to temperature sensing at the alternator, turns down the output voltage and there is no charging ability. This results in a period of negative charging (or ‘deficit motoring’) and it is essential that the alternator/regulator must replace the lost capacity of the battery in further vehicle operation. This means that the highest regulator voltage at low ambient temperatures is required — ensuring, however, that other electrical components (*e.g.*, light bulbs) are not adversely affected — which means a maximum of 15 V.

The hot-climate situation gives the opposite problem. Some of the regulators give significant excess amounts of voltage, in contrast to the cold weather data. This is shown in Table 5 for the same voltage regulators. Figure 5 presents typical charging currents, based on the data of Table 5, for the various alternator characteristics for ambient temperatures of 30 and 40 °C. It can be seen that overcharging of the battery is occurring.

Regular exposure of a battery to temperatures over 60 °C will drastically reduce the service life. The desirable continuous maximum battery temperature is 50 °C with excursions to 60 °C limited to, say, 1 h only. The choice of voltage regulator characteristics must therefore take into account both winter and summer conditions.

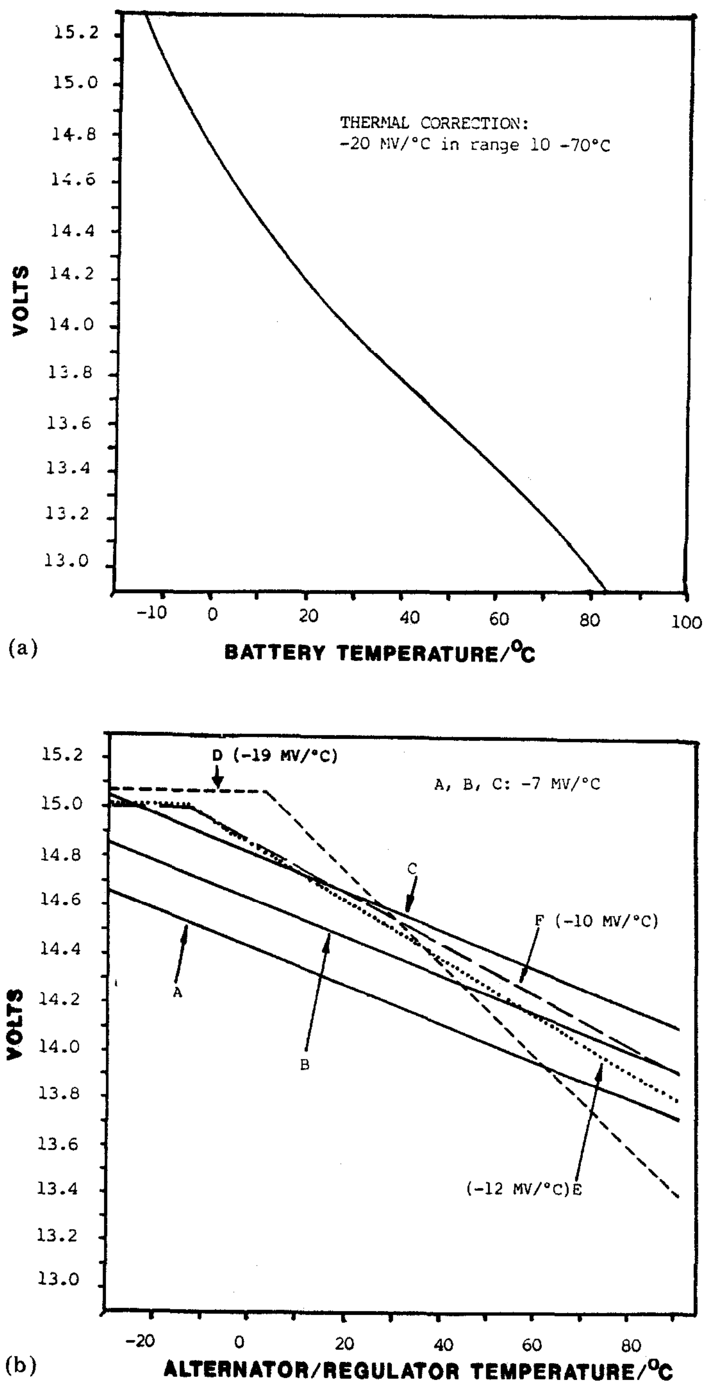


Fig. 4. (a) Repeat of Fig. 3(a); (b) comparison of various proposed regulators with varying thermal correction.

TABLE 4

Performance of various voltage regulators with operational temperature in winter

CONDITIONS – WINTER				MORNING JOURNEY TO WORK			RETURN JOURNEY IN EVENING		
				START	5 min	30 min	START	5 min	30 min
Ambient Temperature (^{0}C)				5	5	6	15	15	15
Battery Temperature (^{0}C)				5	7.5	17.5	15	17.5	27.5
Regulator Temperature (^{0}C)				5	40	55	15	50	75
Required battery voltage to allow 100 mA charge current (V)				14.5	14.45	14.25	14.3	14.25	14.05
REGULATORS									
	Volts at 25^{0}C	Correction factor (mV/^{0}C)	CHARGE	Difference between required and obtained voltage					
A	14.2	-7	YES						
			NO	[0.15]	[0.35]	[0.28]	[0.03]	[0.23]	[0.21]
B	14.4	-7	YES	0.04		0.05	0.18		0
			NO		[0.15]			[0.02]	
C	14.6	-7	YES	0.23	0.05	0.14	0.37	0.17	0.20
			NO						
D	14.6	-19	YES	0.47			0.50		
			NO		[0.15]	[0.25]		[0.15]	[0.40]
E	14.6	-12	YES	0.35		0	0.44	0.05	
			NO		[0.04]				[0.05]
F	14.6	-10	YES	0.30	0	0.05	0.40	0.10	0.05
			NO						

TABLE 5

Performance of various voltage regulators with operational temperature in summer

CONDITIONS - SUMMER				AMBIENT TEMPERATURE 30°C				AMBIENT TEMPERATURE 40°C			
				START	5 min	60 min	120 min	START	5 min.	60 min.	120 min.
Battery temperature (^{0}C)				30	32.5	45	50	40	42.5	55	60
Regulator temperature (^{0}C)				30	65	80	90	40	75	90	100
Required battery voltage to allow 100mA charge current (V)				14.0	13.95	13.7	13.6	13.8	13.75	13.5	13.4
REGULATORS											
	Volts at 25^{0}C	Corr. factor (mV/^{0}C)	CHARGE	Difference between required and obtained voltage							
A	14.2	-7	YES	0.17		0.10	0.14	0.29	0.13	0.24	0.28
			NO		[0.04]						
B	14.4	-7	YES	0.36	0.17	0.32	0.35	0.50	0.30	0.45	0.48
			NO								
C	14.6	-7	YES	0.56	0.36	0.51	0.54	0.70	0.50	0.64	0.67
			NO								
D	14.6	-19	YES	0.50				0.50			
			NO		[0.13]	[0.16]	[0.15]		[0.10]	[0.15]	[0.22]
E	14.6	-12	YES	0.53	0.17	0.23	0.22	0.61	0.25	0.32	0.30
			NO								
F	14.6	-10	YES	0.55	0.25	0.35	0.35	0.65	0.35	0.45	0.45
			NO								

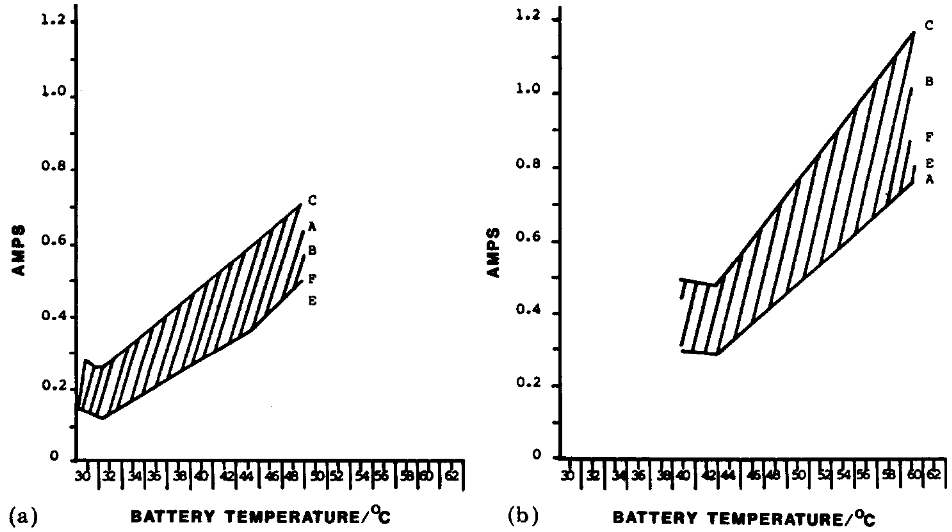


Fig. 5. Range of charging currents arising at ambient temperatures of (a) 30 °C and (b) 40 °C with regulators A - F (refer to Fig. 4 and Table 5).

Regulator F (Fig. 4) appears to offer a possible compromise — but more work has to be done to confirm this, as performance in the cold-weather charging situation is not satisfactory.

As previously stated, the thermal environment of the battery is important. Some contemporary vehicles have engine compartment temperatures over 90 °C. Thermal protection is being included in some vehicles by fitting heat shields or by ducting cool air directly into the battery, and reductions in battery temperature of up to 10 °C have been achieved. A good battery installation should have maximum protection from the radiant heat of the engine.

Situation with temperature compensation

In the above comparisons of voltage regulator and battery relationships, battery temperature was *not* sensed at the alternator. Thermal compensation can only be really effective if it is achieved by reference to battery temperature and not by anticipatory means. This is very desirable for the good health of the battery. Consider now the effect of temperature compensation in relation to the above comparisons of assumed vehicle operation. A further plot is now added to those in Fig. 4(b), that is one in which the regulator temperature is equal to the battery temperature. This plot is shown in Fig. 6(b). The regulator specific point is therefore 14.1 V at 25 °C, and the thermal correction line is at -20 mV $°C^{-1}$, *i.e.*, the same as that for the battery. Under these conditions, the battery is kept at full charge throughout the operational range.

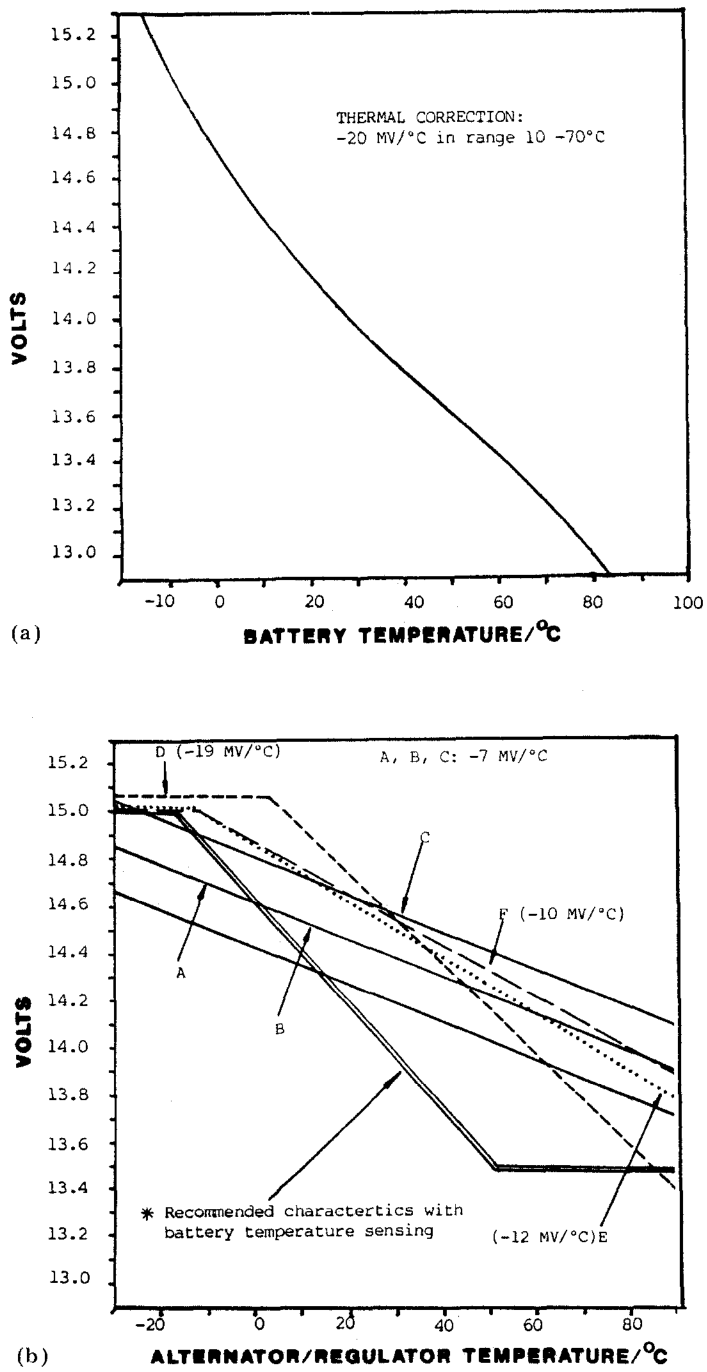


Fig. 6. (a) Repeat of Fig. 3(a); (b) repeat of Fig. 4(b) with characteristic of a regulator with battery temperature sensing.

Alternator/battery relationship

The size of the alternator is usually selected by the vehicle manufacturer, in conjunction with the component supplier, to meet all of the electrical loads and to ensure that the battery remains charged. Ideally, the alternator should be capable of carrying the maximum electrical load on the vehicle at all road speeds, even at idle. Such an alternator would be considerably more expensive than those currently fitted, and it has become universal practice to rely on the battery to supply a proportion of the power required at low engine speeds when high electrical loads are also to be met. Again, the degree to which the battery satisfies the load requirements is critical. Conversely, at higher engine speeds (*e.g.*, a vehicle at 60 km h^{-1}), it is imperative that the alternator output is capable of both maintaining the electrical demand of the vehicle and recharging that energy which has been discharged from the battery at low engine speeds.

The criterion generally adopted is that the battery should be kept above 80% charge under the most severe combinations of high load and low average operational speeds. Every possible factor must be taken into account when designing the system to achieve this objective. In this respect, alternator output voltages are a significant variable. It should be noted that even a high-current alternator will not charge the battery properly if the voltage applied to the battery terminals is not sufficiently high.

Figure 7 shows the output current as a function of alternator speed for two units rated at 70 and 58 A, respectively, together with the electrical loads for two vehicles. The data represent a commonplace situation. At idle, both alternators have outputs of only 46% and are not matching the average electrical load of either vehicle. For example, vehicle ‘A’ has an average load of 40 A and an alternator output of 27 A, *i.e.*, a deficit of 13 A; whilst vehicle ‘B’ has an average load of 48 A and an alternator output of 32.6 A, *i.e.*, a deficit of 15.4 A. The effect of changing the size of the alternator is also abundantly clear. It was actually proposed to use the 58 A alternator on vehicle ‘B’ because of the considerable cost pressure. The result in customer dissatisfaction could be well imagined.

When the average electrical load is above the alternator output, the battery will:

(i) never be fully charged — there will be a walk down in capacity due to progressive sulphation of the active material;

(ii) be subjected to cyclic periods of charge and discharge as engine speed varies from idle to cruise — this will induce shedding of positive-plate material.

To emphasize the real-life situation, the maximum electrical loads on a 3 l Australian passenger car of 1986 design are given in Table 6. A review of the several combinations of load leads to the conclusion that a larger alternator should have been used. During road testing, considerable periods of negative charging were recorded when some lighting and service loads were applied, particularly at low or idle engine speeds.

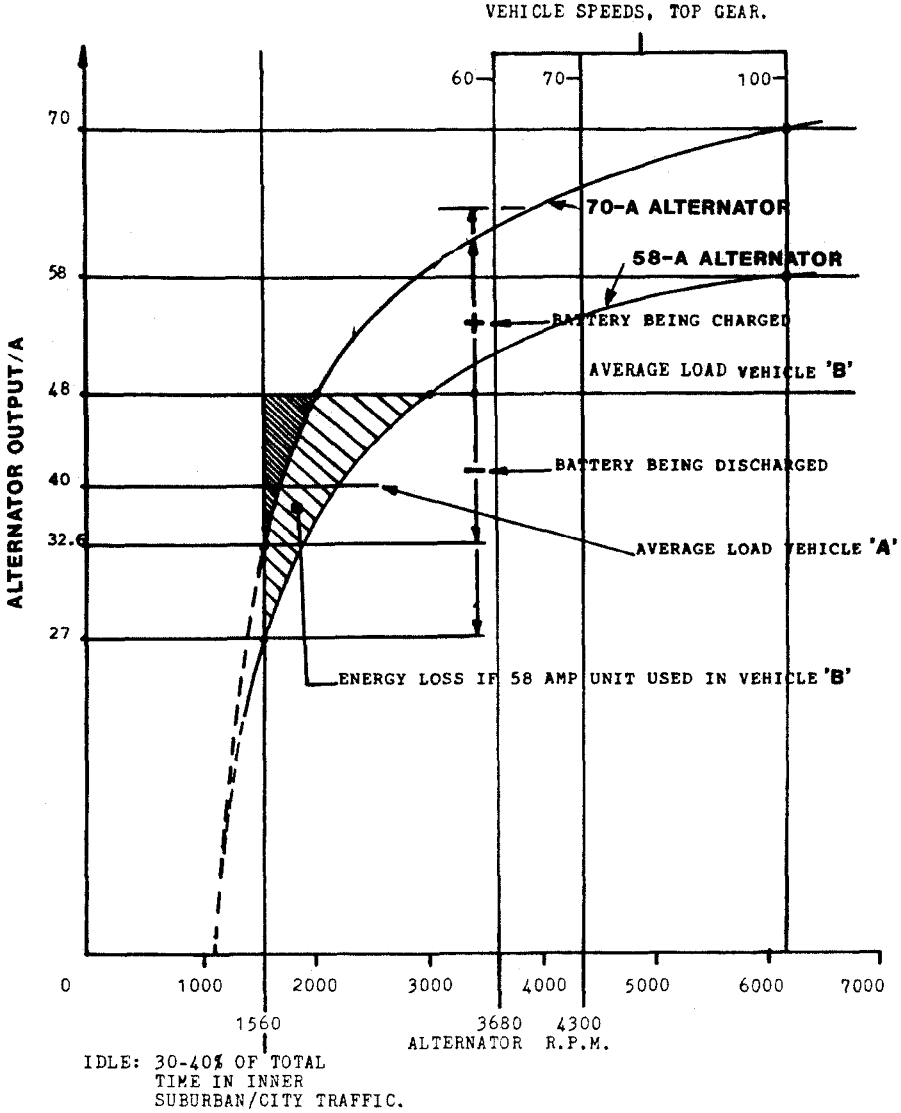
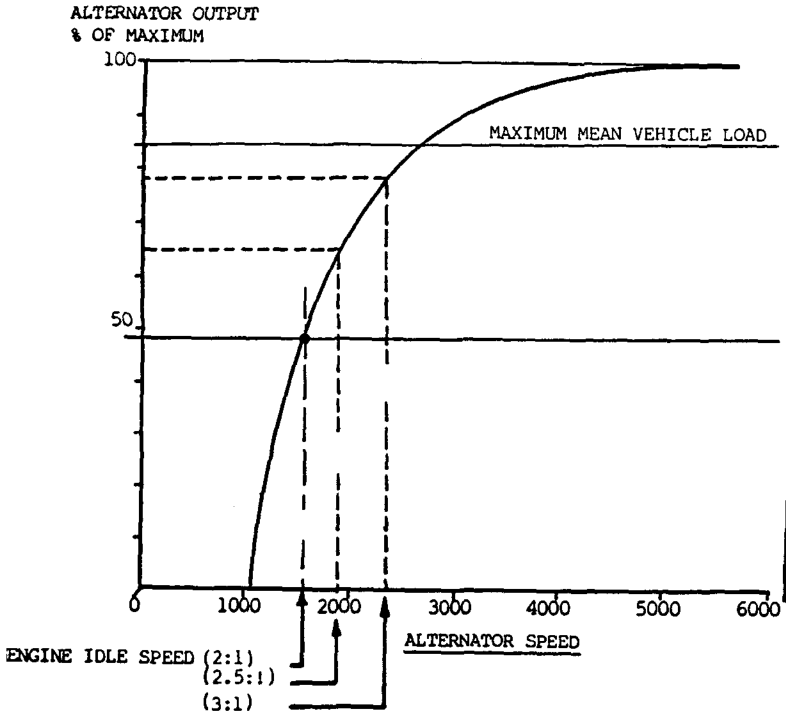


Fig. 7. Alternator performance.

The desired relationship between alternator output and vehicle load is shown in Fig. 8. The data indicate that 80% of the alternator output is available at an alternator speed of 2500 rpm. The rpm at idle is the critical factor and the effect of varying alternator/engine-speed ratios is shown. Ratios of up to 3:1 are to be considered, but regard must be given to the alternator speed at high engine speed. Figure 8 also gives a comparison at idle engine speeds of a 70 A alternator fitted to two vehicles under differing electrical load conditions.



ENGINE RPM IDLE:780 RPM				Data for Idle Output of 70-A Alternator
Alternator/ Engine Ratio	Alternator RPM	% Alternator maximum output	Increase in output (from 2:1)	
2:1	1560	48%	---	33A
2.5:1	1950	66%	38%	46A
3:1	2340	77%	60%	53A

ALTERNATOR : 70 A MAXIMUM OUTPUT				
Ratio		2:1	2.5:1	3:1
RPM		1560	1950	2340
Available output at idle(A)		33	46	53
Conditions	Required Output	Surplus or Deficit		
Vehicle 1		AMPS	AMPS	AMPS
Fine day	24	+9	+12	+29
Wet day/ fine night	44	-11	+ 2	+ 9
Wet night	60	-27	-14	- 7
Vehicle 2				
Fine day	36	- 3	+10	+17
Wet day/ fine night	56	-23	-10	- 3
Wet night	72	-39	-26	-19

Fig. 8. Desired relationships between alternator output and vehicle load.

TABLE 6

Electrical loads (in amperes) on 3 l Australian passenger car of 1986 design

Category	Item	Maximum load (A)	Category total (A)
Engine compartment	Electronic ignition	3	
	Fuel pump	5	
	Engine computer	2	
	Injectors	6	
	Thermo fan (condenser)	8	24
Lighting	Head lamps	18.5	
	Park lamps	5	
	Stop lamps	7	
	Interior	1.5	32
Services	Ventilation fan (including air conditioner)	24	
	Power windows	32	
	Central locking	15	
	Wipers	7	
	Washer	3	
	Cruise control	3	
	Power antenna	4	
	Turn indicators	8	
	Rear window demist	12	108

Note: (i) load supplied by a 70 A alternator; (ii) maximum loads are given in each case.

Starter motor/battery relationship

The relationship between the battery and the starter motor has been the subject of detailed work with the CSIRO Division of Manufacturing Technology. This work has examined the effect of temperature on battery performance during the initial period of engine start-up. The ability of the battery to deliver the required power for starting depends on the state-of-charge of the battery. Although the studies being undertaken are not complete, results to date are having an influence on some of the major car manufacturers in Australia. The up-market versions of one new car to be released in 1988 will now have 95 A alternators fitted. Another company will move away from its previous 14.0 V regulator setting.

Conclusion

The work reported above is intended to emphasize the importance to both battery and automobile manufacturers of discovering in more detail how batteries are used in automotive service. Studies have shown that, at present, most cars are operating with batteries at 50 - 60% of capacity, and that 30% of batteries when replaced are simply ‘flat’. Furthermore, high temperatures are experienced in modern cars, and this environment can destroy batteries quickly. The following action is therefore recommended:

(i) The whole vehicle electrical system must be balanced so that with all electrical loads operating, the battery is always maintained at over 80% of full charge. This requires the alternator to give a high percentage of its full output at low engine speeds.

(ii) The alternator must be able to replace 5% of the battery capacity within 30 min of driving with an average electrical load.

(iii) Alternator sizing must meet the requirements of (i) and (ii) above. The degree of negative charging (deficit motoring) must be strictly limited.

(iv) Even when the alternator has an adequate rated current output, it is essential that there is sufficient potential difference between the battery and the alternator voltage to drive the current through for charging. Large alternators with low voltage are worthless.

(v) Voltage regulation should ideally provide control of both battery-voltage and battery-temperature sensing.

(vi) Recommended voltage regulator specifications are as follows (subject to further development work being carried out):

(a) with both battery temperature and voltage sensing:
specific point: 14.1 V at 25 °C
thermal compensation: -20 mV °C^{-1}

this specification allows the regulator to match the charge-acceptance characteristics of the battery;

(b) with battery voltage sensing only and the voltage regulator working at alternator temperatures:
specific point: 14.6 V at 25 °C
thermal compensation: -10 mV °C^{-1}

(vii) Starter motors must have low impedance and the battery must be fully charged to ensure engine starts in all conditions.

(viii) Overall, the development of a programmed charging system in the vehicle is required incorporating improved voltage regulation (with both battery temperature and voltage sensing) plus charge system diagnosis. This could be an extension to the engine management system.

(ix) Battery size, capacity and cost must be based on the balance determined from:

(a) the cranking performance required, including the rate at which power is to be supplied to the starter;

(b) an adequate capacity for meeting:
- discharge
- parking and other parasitic loads;

(c) the capability to meet any cycling effect of using its capacity as in (b), noting that if smaller batteries are used, the depth-of-discharge will be greater;

(d) the ability to recharge quickly;
(e) the alternator and starter-motor characteristics.

Larger batteries have often been used to cover up deficiencies in the electrical system. Big is not usually best in this context. The proposed requirement (surprisingly coming from a battery manufacturer) is for bigger and more efficient alternators so that automotive batteries can live a long and healthy life.

Acknowledgements

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