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ABBREVIATIONS AND SYMBOLS

a = acceleration, number of pairs of parallel paths
a-c = alternating current
A = frontal area, cross-section, acceleration, surface of the gap
B = brake, magnetic flux density
c = specific heat
C = cruise, cost
C_d = drag coefficient
d-c = direct current
D = bore diameter
DOT = U.S. Department of Transportation
E = electromotive force
ECM = electronically commutated machine
f = frequency
f_B = form factor
f_e = surface density of electromagnetic force
F_e = electromagnetic force
g = acceleration of gravity, effective gap length
g' = physical gap length
G = gradeability
I = current
J = Joule
k_c = Carter factor
k_{cu} = slot filling factor
k_{dp} = winding factor
k_{sa} = saturation factor
K = surface current density
ℓ_{co} = average conductor length
L = inductance, effective bore length
m = actual vehicle mass, meter, number of phases
m* = effective vehicle mass
n = rpm = number of revolutions per minute
N = number of series connected turns

N_{eff} = Nk_{dp} = effective number of turns
OEM = original equipment manufacturer
p = number of pole pairs, tire pressure
P = power
PM = permanent magnet
Q = number of slots, volumetric flow rate
r = gear ratio
rms = root mean square
rpm = number of revolutions per minute
R = resistance
s = second
S = slip, SAE cycle
SAE = Society of Automotive Engineers
SI = International System
t = time, tooth pitch
T = torque
v = velocity
V = voltage
W = weight
X = reactance
Z = number of teeth

α_i = ideal pole face span
γ = electrical conductivity
η = efficiency
θ = temperature rise, grade angle
λ = L_p/t aspect ratio of tooth
μ_o = $4\pi\times10^{-7}$ = permeability of air
ξ = specific weight
π = 3.1416
σ = allowable stress
τ = L/Lm
ϕ = phase angle
Φ = magnetic flux
ω = radian frequency

Subscripts

a	=	armature
ac	=	alternating current
b	=	base
co	=	conductor
cu	=	copper
dc	=	direct current
e	=	electromagnetic, eddy
f	=	field
g	=	gear
h	=	hysteresis
m	=	magnetizing
p	=	peak, pinion
ph	=	phase
p.o.	=	pull-out
R	=	rated
s	=	synchronous
s.c.	=	short circuit
st	=	starting
st,ℓ	=	stray-load
w	=	wheel, windage
1	=	primary
2	=	secondary

Superscript

'	=	referred to the primary

1. Executive Summary

The objective of this study was to compare the efficiency, weight, and cost of various propulsion systems for 4-passenger electric vehicles. These systems comprise the electric motor and the required speed reducing transmission to obtain the appropriate speed at the wheels.

Three types of motors were considered and compared:

- d-c
- synchronous with slip-rings
- squirrel-cage

Two top speeds were selected

- 6000 rpm for the d-c motor
- 24000 rpm for the a-c motor

The peak power considered was in the order of 40 kW.

The types of gearing selected were:

- differential with single speed reduction (no gear change)
- differential with 4-speed gear box.

Approach

To optimize the overall system an original approach to the design of the motor was developed. It takes off from the performance specifications and leads to the dimensions, weight, and cost of the motor, directly, instead of the traditional trial-and-error procedure.

For this purpose the design specifications are cast in the form of analytical expressions which describe the envelopes of the load requirements. In the case of the electric vehicle these are profiles of the "road load" torque and power, as a function of the speed.

Similar torque-speed characteristics are derived for each type of motor, as a function of the terminal voltage and current, and design parameters, such as the gear ratio, the number of turns, and the magnetic flux. These parameters are uniquely determined by equating the torque and power required according to the specifications to those developed by the motor, and by imposing constraints, such as the top speed and peak battery current. Relations between these parameters and the allowable values of the electric and magnetic loadings lead to the main dimensions of the motor. Other analytical expressions were derived to relate these dimensions to the weight, cost, and losses of the motor.

Similarly, analytical expressions were derived for the weight, cost, and losses of the gear, starting from first principles.

The main advantage of approach is its generality. The design procedure is readily applied to new sets of specifications, materials, motor topologies and geometries, constraints, and specific costs.

Results

The main result of the investigation is that for a given battery voltage and peak allowable current the a-c motors develop much less power than their d-c counterparts. This is due in part to the lower ratios of effective to peak values of voltage and current, but mainly to the fact that the power conditioner cannot be by-passed under running conditions. To develop the peak power, then, becomes the most critical requirement and the specified peak power, rather than the starting torque, determines the size of the motor. The a-c motors, then, do not benefit from the reduction in starting torque which the shifting transmission can provide. Because of their higher operating speed, they are also much smaller than the d-c motors and a point of diminishing returns in costs and weight, with diminishing size, is reached.

Similarly with regard to efficiency, the a-c motors are, under running conditions, inherently less efficient than the d-c motors because of the higher current and, therefore, higher copper losses. They can hardly afford additional losses in the shifting transmission even if, conceivably, this could reduce the starting losses.

In contrast, with d-c motors the peak power demand is met without difficulty, and the starting torque is the requirement which determines the size of the motor. The weight and cost of the d-c motor can be reduced by as much as 45%, when a shifting transmission is used. However, for the overall drive the reduction in weight is only 14%, and in cost 30%. The increases in efficiency and range on an SAE J227a Schedule D cycle introduced by the transmission are insignificant.

Energy recovery by regenerative braking is a major factor in the economy of the SAE cycle. With d-c motors, the energy absorbed by the road during the acceleration and cruise phases may exceed the net energy withdrawn from the battery during the whole cycle. By forcing the field, almost 48% of the kinetic energy can be fed back into the battery. In this respect the synchronous motor is at a disadvantage, since the generated current must flow through a rectifier which is separate from the inverter and therefore, adds losses, weight and cost.

Even worse is the situation with the squirrel-cage motor. To operate as a generator it requires a separate excitation in the form of a complex power conditioner of unproven reliability, a synchronous machine, or an adjustable capacitor bank. For this reason, regenerative braking with squirrel-cage motors was not deemed to be practical.

Conclusions

From this preliminary assessment the following tentative conclusions can be drawn:

- A multispeed gear ratio, such as can be realized by means of a shifting transmission, does not seem to improve the performance of the propulsion system in a significant way, even though it may reduce almost by half the weight and cost of the d-c motor.
- The squirrel-cage motor is not suited for vehicles used in urban traffic, because it cannot be easily fitted for regenerative braking.
- The synchronous motor operated in the electronically commutated mode is not yet competitive with the d-c motor, but offers a promising alternative.

Recommendations

It is recommended that:

- This investigation be extended to cover a wide spectrum of specifications, so as to approach the performance of vehicles driven by internal combustion engines in their various applications.
- A greater effort should be devoted to the development of brushless, electronically commutated synchronous motors.

  The major objectives should be

  - adjustable permanent magnet excitation

- increase in the effective voltage of the inverter
- reduction in its weight and cost.

These objectives can be attained by employing new topologies and by designing the electronically commutated machine as a single unit -- the way d-c motors are designed.

2. Performance Specifications

The most stringent among the performance requirements are imposed by safety considerations, such as the need for achieving high accelerations in order to gain access to a thruway and for a high-speed pass maneuver. Particularly demanding is the latter maneuver, which according to DOT[1], would require a total passing distance $\leq$ 1400 feet (427m) covered in a time $\leq$ 15 s, when accelerating from a 50 mph (80 km/h) speed to a limiting speed of 70 mph (112 km/h). The resulting demand in power would exceed the cruising requirements by more than one order of magnitude. Therefore, it is unreasonable to impose such a requirement on the electric vehicle. It has also been observed[2], that the present demand for greater mileage per gallon of gasoline in vehicles driven by internal combustion engines will of necessity entail a reduction of passing maneuverability for all cars. With regard to access to a parkway, no mention of this requirement is made in the "Performance Standards as of March 13, 1980" (see Appendix 1). The specified acceleration rate of 0-50 km/h in 13.5 s is clearly inadequate.

Higher vehicle design goals were set for, and met by the General Electric/Chrysler Near-Term Electric Test Vehicle (ETV-1). These are listed in Table 2.1[3] and were adopted as a basis for this study. The performance specified by the SAE J 227a Schedule D Cycle is described by Figure 2.1.

Two other gradeability performance specifications were added to the one mentioned in Table 2.1. These are:

10% at 25 km/h

20% for 20 s.

TABLE 2.1 ETV-1 Key Performance Objectives

Parameter	DOE Objective
Passenger capacity	4 adults
Curb weight	open
Energy consumption in urban driving	0.5 kWh/mile
Passing speed	60 mph
Cruising speed	55 mph
Acceleration, 0-30 mph	9 seconds
Acceleration, 25-55 mph	18 seconds
Speed on 1 mile 5% grade	50 mph
Urban range (SAE J227/D)	75 miles

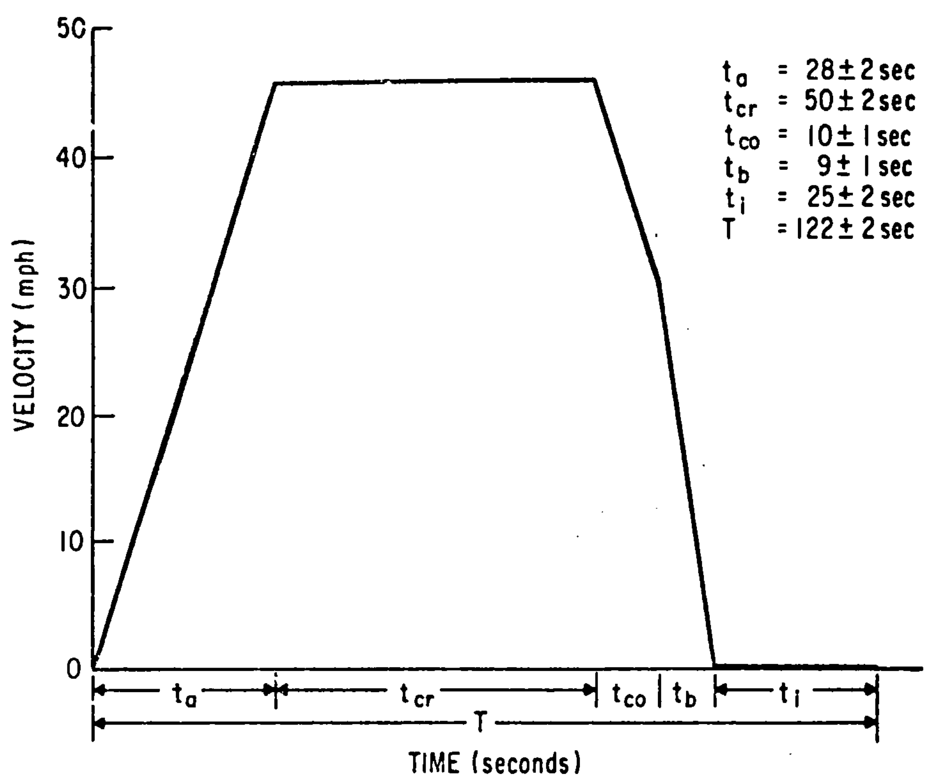

FIG. 2.1 SAE J227a Schedule D Cycle

3. Analytical Models For the Load

The propulsion system must provide the tractive effort to overcome the total "road load" on the vehicle and the losses associated with the power train. The components of the road load are:

- Acceleration
- Gradeability
- Aerodynamic drag
- Tire rolling resistance.

Some uncertainty prevails on how to account for the tire rolling resistance, and various formulas have been used in the literature[4-9]. Equations 3.1 below was derived by curve fitting from data on steel belted radial tires. Accordingly, the overall traction effort is:

$$F = m^{*}a + .6214\ C_d\ A\ v^2 + mg\left(\sin\theta + 5\times10^{-3} + \frac{10^3}{p} + \frac{.36v^2}{p}\right) \qquad (3.1)$$

where

a	=	acceleration
m	=	gross vehicle mass
m^*	=	1.1m for low gear
		1.05m for direct drive
v	=	velocity
C_d	=	drag coefficient
A	=	frontal area
g	=	acceleration of gravity
θ	=	grade angle
p	=	tire pressure

and all quantities are expressed in SI Units. The following parameter values have been assumed:

gross vehicle mass	m	= 1770 kg
drag coefficient	C_d	= .3
frontal area	A	= 1.8 m^2
tire pressure	p	= 221 kPa

The gross mass and the frontal area correspond to those of the ETV-1. The value of drag coefficient was chosen in conformity with recent studies on electric vehicles. It may turn out to be optimistic in view of the fact that tests performed in connection with the development of the 1981 models gave .417 for G.M.'s Citation and .4 for Ford's Escort/Lynx. The value assumed for the tire pressure (32 psi) is a little on the high side, if one considers passenger comfort, but was chosen because the electric vehicle will be used mainly at low speed in urban traffic. At any rate the contribution of the pressure dependent terms of the rolling resistance is not significant.

Application of Eq. 3.1 to the performance specifications of the previous section leads to the wheel torques T_w in Fig. 3.1 and the motor powers P in Fig. 3.2, as a function of wheel rpm n_w. The torques are based on a wheel radius of .28m corresponding to steel belted radial tires AR 78-13. Both torque and power requirements have been augmented by 4% to account for losses in the differential and axle[4]. The data points marked A correspond to the thruway access acceleration requirement

$$a = 1.9 \exp[-.065t] \tag{3.2}$$

This leads to the desired speed of 88 km/h (55 mph) in 28s. It also satisfies the separate requirements of acceleration from 0 to 30 mph in 9s and the thruway merging duty acceleration from 25 to 35 mph in 18s. An exponentially decaying acceleration was chosen,

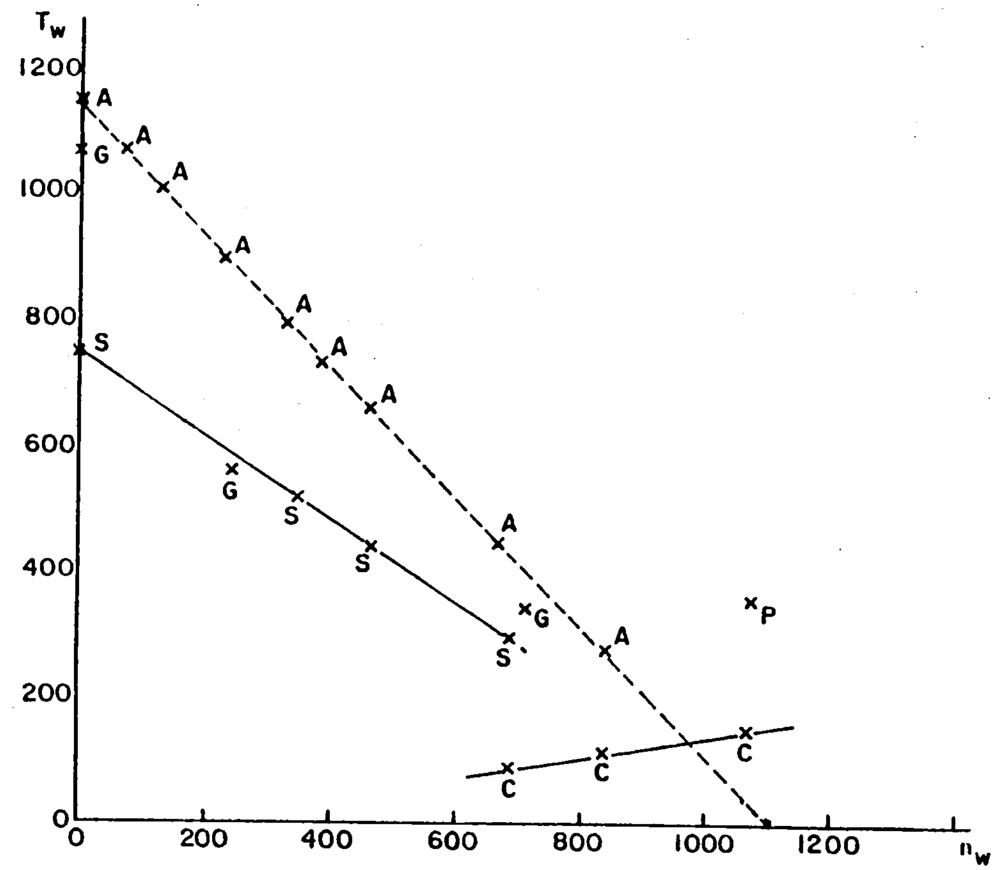

Fig. 3.1 Augmented Wheel Torque as a Function of the Wheel RPM

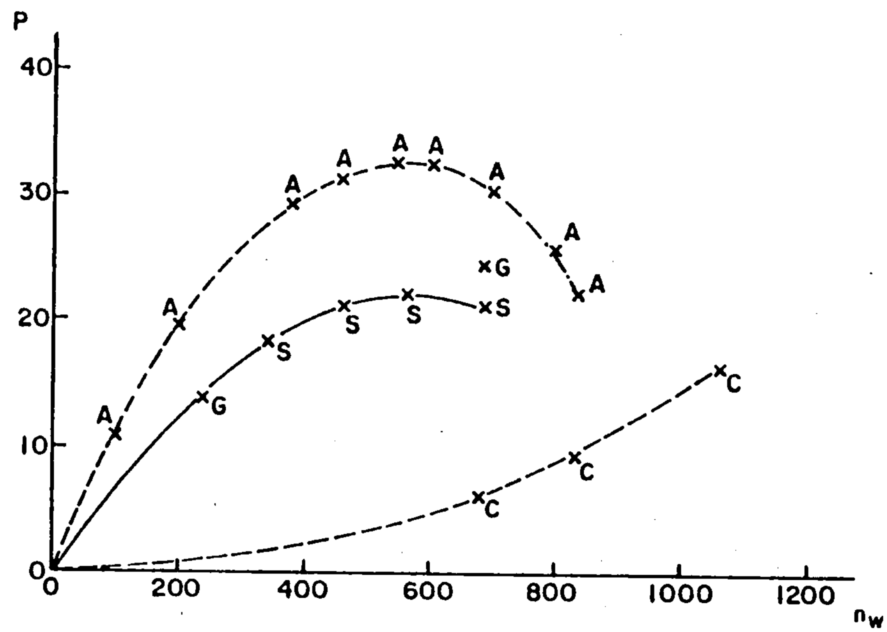

Fig. 3.2 Augmented Wheel Power as a Function of the Wheel RPM

rather than a constant one, in order to reduce the peak power drawn from the battery at the expense of a somewhat more stringent requirement on the torque developed by the motor at starting.

The data points marked S correspond to the SAE cycle acceleration requirement

$$a - 1.22 \exp[-.042t] \qquad (3.3)$$

It leads to the desired 72 km/h speed in 28s. As the data points marked G indicate, the gradeability requirements fall well within the acceleration torque and power envelopes. Finally the data points marked C indicate the cruise requirements.

It is interesting to note that the torque points A, S, and C lie approximately on straight lines and, therefore, lead to convenient analytical expressions as follows:

$$T_{wA} = 1139 - 1.035\, n_w \qquad (3.4)$$

$$T_{wS} = 749 - .663\, n_w \qquad (3.5)$$

$$T_{wC} = .14\, n_w \qquad (3.6)$$

The corresponding powers are:

$$P_A = \frac{2\pi}{60} n_w\, T_{wA} = 119.25\, n_w - .108\, n_w^2 \qquad (3.7)$$

$$P_S = \frac{2\pi}{60} n_w\, T_{wS} = 78.42\, n_w - .069\, n_w^2 \qquad (3.8)$$

$$P_C = \frac{2\pi}{60} n_w\, T_{wS} = .0146\, n_w^2 \qquad (3.9)$$

According to the SAE cycle the car has to be brought to a halt from 72 km/h in 19s. Part of the kinetic energy can be fed back by operating the propulsion system in the generating mode. Again, in order to avoid a large peak of power, the deceleration rate has been chosen to vary exponentially as:

$$a = -\ .5\ \exp[.071t] \qquad (3.10)$$

The corresponding wheel torque is

$$T_{wB} = -974.33 + 1.16\ n_w \qquad (3.11)$$

and the corresponding power is

$$P_B = -\ 102\ n_w + .1214\ n_w^2 \qquad . \qquad (3.12)$$

4. Motor Types Selected for Consideration

Motors used in electric traction are usually called to develop their maximum torque at starting. For this reason the most popular type is the d.c. motor. The advent of efficient speed controls by means of solid-state switching elements has recently favored separate excitation over the more traditional series excitation. The main advantage is better efficiency and higher operational flexibility.

The major hurdle in heteropolar variable speed drives is the need to feed the active conductors at a frequency which matches their speed. This necessitates the introduction of switching elements and, since the motor circuits are inductive, creates commutation problems.

In d-c motors the change in frequency is accomplished by an array of mechanical switches called commutators. Its main drawback is the limitations it poses on the motor speed, thus preventing reduction of the motor size, weight, and cost. In addition, the presence of sliding contacts through soft carbon brushes necessitates frequent maintenance. A big forward step in automotive technology was achieved when the d-c machine, used as a generator, was substituted by a synchronous one. The same type of machine, when fed by a variable frequency inverter, can also be employed for the propulsion of an electric vehicle. When the firing angle of the switching elements is governed by sensing the position of the poles in a closed-loop control fashion, the synchronous machine duplicates the performance of the d-c machine and is called an electronically commutated machine (ECM). This motor can be operated at much higher speed than its d-c counterpart and, therefore, is much lighter and cheaper, but the inverter is heavier and more expensive than the commutator. Moreover, the inverter, which contains at least six times as many switching elements as the chopper that feeds the d-c machine, must remain connected under all conditions of operation, whereas the chopper is needed only in the starting phase. Also, to take advantage of regenerative braking, a separate rectifier must be added, or bidirectional switching elements, such as Triac's must be used, further increasing the weight and cost of the power conditioning units.

The synchronous machine can be made brushless either by using magnetic circuits having complex topologies, such as in the case of Lundell, Rice and Lorentz types, or by resorting to permanent magnet (PM) excitation. Complex topologies, in general, imply heavy weight; PM excitation requires mechanical field adjustments, if it is desired to retain the ability of controlling the speed with some power gain and in order to avoid excessive core losses at rated cruising speed.

To overcome the drawbacks of PM excitation, the author of this report has devised two new types of brushless machines. The first utilizes a hybrid PM/current excitation scheme which can be positively or negatively compounded[10], the other uses a topology specifically designed to allow fabrication of the armature core with low-loss, amorphous metal ribbons and to reduce the manufacturing cost of the motor.

Since all these machines need further development, the present study deals only with synchronous motors having field excitation coils located in the rotor and fed through sliprings. This is the type which was adopted by the automotive industry for use as an alternator and which by now has to its credit many years of satisfactory performance.

The rotor coils can also be fed inductively and replaced by a squirrel cage winding. The resulting type -- the induction motor is the most common, rugged and cheap type of electric motor. Its drawbacks are:

(1) It cannot provide its own magnetization needs.

(2) It is singly excited.

From (1) follows that when the induction motor is used for electric propulsion, the power conditioner cannot be commutated naturally and regenerative braking cannot be realized without the addition of complex power electronic circuits and controls, an adjustable capacitor bank, or a synchronous condenser. The major difficulty in using the power conditioner to transfer VAR's in one direction and Watts in the opposite one, simultaneously, stems from the tight requirements with regard to the magnetic flux level in the iron cores and from the need to maintain a smooth and stable preprogrammed deceleration profile.

From (2) follows that the starting torque is limited by the fact that the rotor current cannot be forced beyond the value which is induced by the saturation value of the magnetic flux density. No significant increase in developed torque is achieved by forcing through the stator winding a current in excess to the one which brings the iron into saturation. The excess current would be out of phase with the induced magnetic field. To further clarify this point and to reach a comparative evaluation of the three machine types a brief review of the fundamental principles is given in the next section.

5. Motor Weights and Costs

The torque developed in an electrical machine of the magnetic type can be viewed as resulting from the interaction between the current flowing in the active conductors and the magnetic field prevailing in the air gap which separates the stator from the rotor[11].

Under ideal conditions the current flowing in the conductors is sinusoidally distributed along the periphery of the gap and, for the purpose of analysis, can be replaced by a surface current density wave $\bar{K}$. Ideally, the magnetic field is also sinusoidally distributed and can be represented by the flux denxity $\bar{B}$. The force acting on the conductors per unit surface of the gap, f_e, is given by the phasor product

$$f_e = Re[\bar{K}\cdot\bar{B}^*] \quad . \tag{5.1}$$

In this product the factor K, which is limited by thermal considerations, can be taken as an index of the "electric loading" and B, which is limited by iron saturation, becomes an index of the "magnetic loading." The total electromagnetic force is

$$F_e = f_e A = A\ Re[\bar{K}\cdot\bar{B}^*] \tag{5.2}$$

where $A = \pi DL$ = surface of the gap

D = bore diameter

L = effective bore length.

The developed torque is:

$$\begin{aligned} T &= \frac{D}{2}F_e = \frac{\pi}{2}\ D^2L\ Re[\bar{K}\cdot\bar{B}^*] \\ &= \frac{\pi}{2}\ D^2L\ KB\ \cos\ (\widehat{KB}) \end{aligned} \tag{5.3}$$

It appears that for given dimensions and given values of K and B the maximum torque obtains when the $\bar{K}$ and $\bar{B}$ waves are in phase. The actual values of K and B depend on the machine type, its application and the number of its poles. As a general trend, their product, i.e., f_e, increases with the dimensions of the machine and, therefore the volume D^2L tend to increase more slowly than the torque T.

The quantity of interest in determining the frame size is not the bore diameter D but the outside diameter D_o. Also the torque T is more conveniently expressed in terms of the ratio of the power output (kW or kVA) and the speed (rpm).

The following relations then obtain for machines in the power and speed ranges suited for electric vehicles:

$$D_o^2L = \begin{cases} .66\left(1+\frac{.42}{p}\right)\left(\frac{kW}{rpm}\right)^{.75} & \text{for d-c motors} \\ .3\left(1.1+\frac{.7}{p}\right)^2\left(\frac{kVA}{rpm}\right)^{.8} & \text{for synchronous motors} \\ .5\left(1+\frac{1}{p^2}\right)\left(\frac{kW}{rpm}\right)^{.8} & \text{for squirrel cage motors} \end{cases} \qquad (5.4)$$

where p = number of pole pairs.

The coefficients which appear in front of the parenthesis are indicative of the electric and magnetic loadings and are derived on the basis of conservative designs for continuous-time ratings.

Once the frame size has been determined on the basis of the D_o^2L product, one can derive the following relations for W, the total weight of the machine expressed in kg.

$$
W = \begin{cases} 1900(1+\frac{.1}{p})(\frac{kW}{rpm})^{.58} & \text{for drip-proof d-c motors} \\ 1200(1.1+\frac{.2}{p})^2(\frac{kW}{rpm})^{.6} & \text{for drip-proof synchronous motors} \\ 740(1.1+\frac{.4}{p})^2(\frac{kW}{rpm})^{.57} & \text{for totally enclosed synchronous motors} \\ 1100(1+\frac{.24}{p^2})(\frac{kW}{rpm})^{.6} & \text{for drip-proof squirrel cage motors} \\ 950(1+\frac{.47}{p^2})(\frac{kW}{rpm})^{.57} & \text{for totally enclosed squirrel cage motors} \end{cases} \quad (5.5)
$$

These weights do not include the fan, since for electric vehicle applications it is desirable to employ separate blowers.

The cost of a given type motor is usually proportional to the weight. The following specific costs expressed in 1976$ per kg weight have been derived and used in this study.

$$
C = \begin{cases} 7 \ \$/kg & \text{for d-c motor} \\ 5.5 \ \$/kg & \text{for drip-proof synchronous motor} \\ 5 \ \$/kg & \text{for totally enclosed synchronous motors} \\ 4.5 \ \$/kg & \text{for drip-proof squirrel cage motors} \\ 4.25 \ \$/kg & \text{for totally enclosed squirrel cage motors.} \end{cases} \quad (5.6)
$$

A word of caution is in order regarding these weights and costs. The weights are derived on the basis of continuous-time ratings for machines of conservative design. They are consistent with those of the ETV-1 motor and other traction motors, but are much higher than those quoted in Ref. 4. The same is true regarding the prices. They represent reasonable estimates of the original equipment manufacturer's (OEM) costs and are consistent with the cost quoted for the ETV-1 motor[12]. They are, however, twice as high as the costs quoted in Ref. 4.

Finally both Refs. 4 and 12 give 1.4 as a markup factor to arrive at the suggested selling price. Judging from the actual selling prices of electric motors, this factor seems to be grossly underestimated.

6. D-C vs. A-C Motors

The continuous-time rating is not the only criterion for the design of a traction motor, because of the high torque which is required at starting. Also each motor type differs in its torque speed characteristics. In order to compare the performance of different motors, the effective electric and magnetic loading are assumed to be equal.

To begin with the electric loading, K is related to the current I. In a d-c motor the relation is

$$K = \frac{2NI}{\pi D} \tag{6.1}$$

where N is the number of series connected turns and I is the armature current, and its effective value coincides with its constant value.

In an a-c machine one has:

$$K = \frac{2mN_{eff}I}{\pi D} \tag{6.2}$$

where m is the number of phases, N_{eff} is the number of series connected turns per phase multiplied by the winding factor k_{dp}. The current I is the effective value of the phase current I_{ph}. In the case of an inverter supply its value ranges from $I_{dc}/\sqrt{2}$, for a sinusoidal waveshape, to $\sqrt{\frac{2}{3}}\, I_{dc}$, for a rectangular wave with a 120° conduction period.

Next one considers B. In a d-c motor the effective value is its average value, which is related to the peak value B_p as

$$B = \alpha_i B_p \tag{6.3}$$

where α_i is essentially the ratio of the pole face length to pole pitch. The angle between K and B can be considered to be zero. In an a-c motor the effective value of B is its rms value. Its relation with B_p is usually expressed as

$$B = f_B \alpha_i B_p \tag{6.a}$$

where $f_B = \frac{B_{rms}}{B_{ave}}$ = form factor

$$\alpha_i = \frac{B_{ave}}{B_p} \tag{6.5}$$

It follows that if the d-c and a-c machine have the same dimensions, the same effective number of turns ($N = m N_{eff}$), and the same B_p, their developed torques are related by

$$\frac{T_{ac}}{T_{dc}} = \frac{(f_B \alpha_i)_{ac}}{(\alpha_i)_{dc}} \frac{I_{rms}}{I_{dc}} \cos(\widehat{IB}) \tag{6.6}$$

The phase angle $\widehat{IB}$ can be made exactly zero in a synchronous motor. It can be made quite small also in a squirrel-cage motor by varying the frequency, so as to maintain a small value of slip. The ratio T_{ac}/T_{dc} is then in the order of 3/4.

Other useful relations are obtained by introducing the flux per pole

$$\Phi = \frac{\pi DL}{2p} B = \frac{E}{4fN} \tag{6.7}$$

where E = electromotive force

$f = pn/60 =$ frequency.

They are:

$$T_{dc} = \frac{2}{\pi} Np \, \Phi \, I_a \tag{6.8}$$

and

$$T_{ac} = \frac{2}{\pi} m \, N_{eff} \, p \, \Phi \, I_{ph} \cos(\Phi I_{ph}) \quad . \tag{6.9}$$

7. Design Principles for the D-C Motors

Each motor type is governed by a specific relation between voltage V and the current I. In a d-c motor this is:

$$I = \frac{V-E}{R} - \frac{V-4fN\Phi}{R} \tag{7.1}$$

where R is the total resistance of the armature circuit.

At starting the current is V/R and, in order to limits its value, V should be reduced. Equation (6.8) also shows that, in order to develop the highest possible torque for a given current, the flux Φ should be as high as possible, i.e., forced into saturation.

As the motor picks up speed, the voltage is increased until it reaches its nominal value. The corresponding speed depends on the load torque and is called <u>base speed</u>. Further increases in speed are achieved by weakening the field. The motor and wheel torque and speed are related by the gear ratio r:

$$T = \frac{T_w}{r} \; ; \qquad n = r\, n_w \tag{7.2}$$

Introducing Eqs. (7.1) and (7.2) into Eq. (6.8) and using the definition of f from Eq. (6.7), one obtains

$$T_w = \frac{2}{\pi}(rNp\Phi) \, \frac{V - \frac{4}{60}(rNp\Phi)n_w}{R} \tag{7.3}$$

and

$$P = \frac{2\pi}{60} n_w T_w = \left(\frac{4}{60} rNp\Phi\, n_w\right)\frac{V}{R} - \left(\frac{4}{60} rNp\Phi\, n_w\right)^2 \frac{1}{R} \tag{7.4}$$

where the torque and power must at all times match those required by the load, according to Eqs. (3.4) to (3.9), (3.11) and (3.12). It appears that the main design problem is: how to split the product ($rNp\Phi$) into its components.

Considered first is the case of a fixed gear ratio r. Since the product $p\Phi$ is proportional to the area of the gap and, hence, to the dimensions of the machine, it is clear that it is desirable to make r as high as possible. The limiting factor is, then, the permissible speed of the motor at the highest vehicle speed. At the passing speed of 112 km/h (70 mph), n_w is 1067, therefore, if n_{max} indicates the maximum allowable motor speed, the gear ratio is:

$$r = \frac{n_{max}}{1067} \tag{7.5}$$

A fixed gear ratio imposes severe demands on the starting performance of the motor, because the maximum starting torque is uniquely determined as

$$T_{st} = \frac{(T_{wA})_{st}}{r} = \frac{1139}{r} \tag{7.6}$$

If T_{st} is chosen as the determining factor for the bore dimensions, these can be obtained from Eq. (5.3), by assuming limiting values for K and B.

The aspect ratio is approximately

$$L/D = \frac{\pi}{2} p^{-2/3} \tag{7.7}$$

To determine Φ one must choose p. The main tradeoff is: high copper losses, because of long end-winding connections, when the number of poles is small, vs. high core losses, due to the high frequency, when the number of poles is large.

In general the number of pole pairs obeys the linear relation[13]:

$$p = 1 + 2.9D \tag{7.8}$$

Chosen p to the nearest integer, the saturation flux is determined. The only undetermined parameter is the number of turns N. This can be found from Eqs. (7.3) and (3.4) by selecting a value for the base speed n_{wb}. The trade-off is: a high starting current, because of a small N when n_{wb} is large, vs. large ohmic losses during cruising, because of large I when n_{wb} is small. A good starting guess for thruway access acceleration is

$$n_{wb} = \frac{1067}{4} = 266 \tag{7.9}$$

In the field weakening regime the needed flux level is obtained from Eq. (7.3) and is given approximately by

$$\Phi \simeq \frac{\pi}{2rNp} \frac{V}{\frac{2\pi}{60} n_w} - \frac{T_w}{V/R} \tag{7.10}$$

and the corresponding current by

$$I \simeq \frac{P}{V}(1 + \frac{R}{V^2} P) \tag{7.11}$$

Finally, in order to be able to make comparisons with Eq. (5.4), the outside diameter can be taken to be

$$D_o = 2.1D \tag{7.12}$$

The shifting transmission effectively decouples the starting from the cruising performance. The motor can, then, be designed to produce the desired peak power, rather than torque, and its size and cost are reduced. It is also possible to reduce the top speed and the flux swing, thus improving the efficiency. Lower peak current demands are imposed on the battery. The gear ratios are determined by setting upper bounds to the battery current and motor speed.

8. Design Principles for the Synchronous Motors

The design of the synchronous motor proceeds along lines similar to those of the d-c motor. The armature current is given by

$$\dot{I} = \frac{\dot{V} - \dot{E}}{R_a + j2\pi f L_a} = \frac{\dot{V} - 4fN\dot{\Phi}}{R - j\,\omega L_a} \qquad (8.1)$$

where R_a = armature resistance

L_a = leakage inductance of the armature,

ω = radian frequency

$\dot{I}$ = runs value of the phase current and

$\dot{V}$ = runs value of the phase voltage

and the dot stands for time-phasor.

The phase voltage is much smaller than in the case of the d-c machine, because two phases are connected in series and the effective value is a fraction of the peak value. Besides, as mentioned in Sec. 4, the full battery voltage cannot be made available at the end of the starting maneuver, because the power conditioner cannot be by-passed. This means a voltage reduction, because of saturation below the 100% level and a voltage drop across the two series connected switching elements.

As a result of the lower available voltage, the current drawn from the battery, for equal power output, is larger than in the d-c motor. The peak power output, which for the thruway access acceleration reaches a value of 33 kW at n_w = 550 rpm, becomes the factor determining the bore dimensions.

For a fixed gear ratio r, determined as before by the maximum allowable speed of the motor during the passing maneuver, the peak motor torque is specified. The bore dimensions are, then, derived from Eq. (5.3). The aspect ratio L/D can be chosen as 1.25. The number of turns N is obtained from the assumed value of K and introducing

$$I = \frac{P}{m\ V\ \cos\phi} \tag{8.2}$$

into Eq. (6.2). The power factor $\cos\phi$ can be made equal to unity. The required starting current should be checked, but it is not likely to exceed the peak power current.

An important conclusion can now be drawn from the fact that the synchronous drive is "power limited" at about 50% of the top speed.

Since the power is independent of the gear ratio, the introduction of a shifting transmission cannot have a significant effect on the current I and, hence, on the ohmic losses. Also, judging from Eq. (5.6) and the rather weak dependence of the motor weight on rpm, the transmission cannot appreciably reduce the weight of the motor. It should be noted, in this regard, that the synchronous motor, even with fixed gear, is much lighter than the d-c motor, because of the higher allowable speed, and weighs only about 50 lbs.

Finally the ratio of outside to bore diameter is approximately

$$\frac{D_o}{D} = 1.3 + \frac{.7}{p} \tag{8.3}$$

9. Design Principles for the Squirrel-Cage Motors

The squirrel-cage induction motor is subject to the same limitations with respect to voltage as the synchronous motor. In addition, as was mentioned in Sec. 4, it cannot be force-fed during starting. For this reason its starting performance will be examined in detail.

The performance of the squirrel-cage motor can be described by the following set of equations[14]:

$$\dot{V}_1 = (R_1 + j\,\omega\,L_1)\,\dot{I}_1 + \dot{E} \tag{9.1}$$

$$O = (R_2' + j\,S\,\omega\,L_2')\,\dot{I}_2' + S\dot{E} \tag{9.2}$$

$$\dot{E} = j\,\omega\,L_m\,(\dot{I}_1 + \dot{I}_2') \tag{9.3}$$

where

R_1	=	primary resistance
R_2'	=	secondary resistance referred to the primary
L_1	=	primary leakage inductance
L_2'	=	secondary leakage inductance referred to the primary
L_m	=	magnetizing inductance
ω	=	radian frequency
$\dot{V}_1$	=	primary phase voltage
$\dot{I}_1$	=	primary phase current
$\dot{I}_2'$	=	secondary current referred to the primary
S	=	$\frac{n_s - n}{n_s}$
n	=	rpm
n_s	=	$\frac{60}{2\pi} \times \frac{\omega}{p}$ = rpm at synchronism

These can be represented by the equivalent circuit of Fig. (9.1).

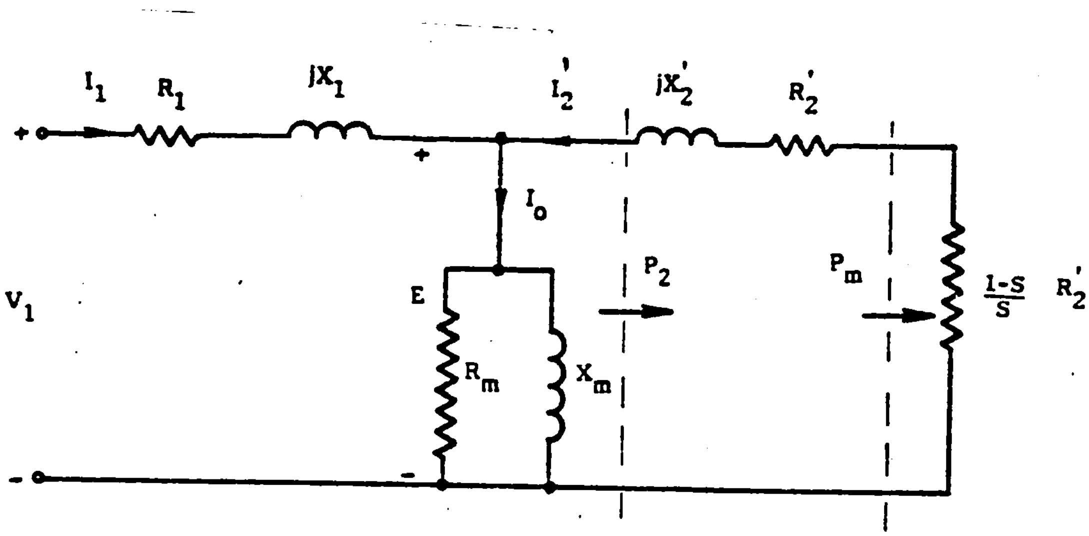

Fig. 9.1 Equivalent Circuit of Squirrel-Cage Motor

The torque is given by

$$T = \frac{m_1 R_2' I_2'^2}{S\, \omega/p} \tag{9.4}$$

is a function of S and peaks when

$$S = S_{p.o.} = \sqrt{\frac{(1+\tau_1)^2 R_2'^2 + (\frac{R_1 R_2'}{\omega L_m})^2}{\omega^2 L_{s.c.}^2 + (1+\tau_2)^2 R_1^2}} \tag{9.5}$$

where $S_{p.o.}$ = pull-out slip

$\tau_1 = \frac{L_1}{L_m}$

$\tau_2 = \frac{L_2'}{L_m}$

$L_{s.c.} = L_1 + (1+\tau_1) L_2'$

Assuming that

$$(1+\tau_1)R_2 \approx (1+\tau_2)R_1 \tag{9.6}$$

the frequency for which the pull-out torque occurs at stalling (S=1) is

$$\omega = \sqrt{\frac{R_1 R_2}{L_m L_{s.c}}} = \frac{1}{L_m} \cdot \frac{\sqrt{R_1 \cdot R_2}}{\sqrt{\tau_1+(1+\tau_1)\tau_2}} \tag{9.7}$$

The resulting torque can be expressed in terms of the bore dimensions and primary current by introducing

$$\dot{I}_1 = [S(1+\tau_2) - j\, R_2'/S\omega L_m]\dot{I}_2' \tag{9.8}$$

and

$$L_m = \frac{\mu_o m_1 (N\ k_{dp})^2 DL}{\pi p^2 g}$$

where

μ_o = permeability of air = $4\pi\times10^{-7}$

g = $k_{sa}\ k_c\ g'$ = effective air gap length

k_{sa} = saturation factor

k_c = Carter factor

g' = physical gap length.

The starting torque then becomes:

$$T_{st} \simeq \frac{(m_1\ N\ k_{dp})^2}{\pi p} \frac{\mu_o DL}{g} \frac{\sqrt{\tau_1 + \tau_2}}{1+\tau_1+3\tau_2}\ I_{1st}^2 \tag{9.9}$$

A second relation, obtained by introducing

$$\dot{I}_2' = \frac{\dot{E}}{\sqrt{\frac{R_2'}{S} + \omega^2\ L_2'^2}} \tag{9.10}$$

and by using Eq. (6.7), is

$$T_{st} \sim 2p(\pi DLg)(B^2/2\mu_o)\ \frac{1}{\sqrt{\tau_1+\tau_2}}\ \frac{1}{1+\frac{\tau_2^2}{\tau_1+\tau_2}} \tag{9.11}$$

It now appears that, in an induction motor, B and I and, therefore, K cannot be chosen independently.

Equating Eqs. (9.9) and (9.11) and using Eq. (6.2) one obtains:

$$B_{st} = \frac{\mu_o m_1 N k_{dp}}{\pi p g} \sqrt{\frac{\tau_1 + \tau_2}{1+\tau_1+3\tau_2}} I_{st} = \sqrt{\frac{\tau_1 + \tau_2}{1+\tau_1+3\tau_2}} \frac{\mu_o D}{2pq} K_{st} \qquad (9.12)$$

The check on the starting torque, then, involves a check on both the starting current I_{st} from Eq. (9.9) and on B_{st} from Eq. (9.12).

The ratio of outside to inside diameter is approximately

$$\frac{D_o}{D} = 1.33 + \frac{.8}{p} \qquad . \qquad (9.13)$$

10. Evaluation of the Motor Losses

The major losses, under rated conditions of operation, usually occur in the copper and can be calculated from Eqs. (7.11), (7.12), (9.8) and (9.10) for the current I, once the appropriate resistance R is known.

The resistance of the armature winding in a d-c machine is

$$R = \frac{2N\ell_{co}}{(2a)^2\gamma A_{co}} \tag{10.1}$$

where ℓ_{co} = average length of conductor

$\simeq 1.2 + \frac{2D}{pL}$

2a = number of parallel paths

γ = electrical conductivity

A_{co} = cross section of conductor

An estimate for the conductor cross-section can be obtained as

$$A_{co} = \frac{k_{cu}\ A_{slot}}{4Na} = \frac{.5\pi(.7D+1.5\times10^{-7}K_{st})1.5\times10^{-7}K_{st}}{4Na} \tag{10.2}$$

where $k_{cu} \approx .5$ is the slot filling factor.

Similarly the resistance of one phase winding in an a-c machine is:

$$R = \frac{2N\ell_{co}}{\gamma A_{co}} \tag{10.3}$$

where $\ell_{co} \simeq L + .03 + \frac{2D}{p}$

$$A_{co} = \frac{.5\pi(.7D+1.5\times10^{-7}K_{st})1.5\times10^{-7}K_{st}}{2mN} \tag{10.4}$$

Other approximate formulas give the copper loss directly. For d-c motors the armature loss is:

$$P_{cu\ a} \simeq 2.54\times10^3 DL(1.2+\frac{2D}{pL})(rpm)^{\cdot 2}\ (\frac{T}{T_R})^2(\frac{\phi_R}{\phi})^2 \qquad (10.5)$$

where R stands for rated.

In general, the forced flux at starting is

$$\phi_{st} = 1.3\ \phi_R \qquad (10.6)$$

The armature loss should be augmented to account for the brush contact loss by an amount

$$P_{br} = 0.024\ P_R \qquad (10.7)$$

The field loss in d-c and synchronous motors is:

$$P_{cu\ f} = 1.3\times10^3 DL(1.2 +\frac{2D}{pL})(rpm)^{\cdot 2}\ (\frac{I_f}{I_{fR}})^2 \qquad (10.8)$$

where the field current at starting can be assumed to be

$$I_{f\ st} = 2\ I_{fR}. \qquad (10.9)$$

In an a-c winding the copper loss is

$$P_{cu\ 1} = 2.156\times10^3 DL(1.3 +\frac{2}{p}\frac{D}{L})(rpm)^{\cdot 2}\ (\frac{T}{T_R})^2 \qquad (10.10)$$

In a squirrel-cage rotor the loss is

$$P_{cu\ 2} \simeq S\ P = [1 - \frac{rpm}{(rpm)_s}]P \qquad (10.10)$$

and the total copper loss

$$P_{cu\ 1} + P_{cu\ 2} = [(1+\tau_2)^2 +\frac{R_1}{R_2}]\ [1- \frac{rpm}{(rpm)_s}]P \qquad (10.12)$$

Next come the core losses, which have an hysteresis component (P_h) and an eddy-current component (P_e) and depend on the type of the laminations.

Based on the data of Ref. 15, the following formulas were derived:

For AISI Type M-27 laminations:

$$P_h = 0.019 \; f \; B_p^2 \; [W/kg] \tag{10.13}$$

$$P_e = 6.2{\times}10^{-4} (\Delta f B_p)^2 \; [W/kg] \tag{10.14}$$

where Δ is the lamination thickness

and for AISI Type M-15 laminations

$$P_h = 0.016 \; f \; B_p^2 \; [W/kg] \tag{10.15}$$

$$P_e = 8.79{\times}10^{-4} (\Delta f B_p)^2 \; [W/kg] \tag{10.16}$$

With these relations the core losses in the rotor of the d-c machine, assuming laminations .47 mm thick, become:

$$P_h = 6 \; D^2 L \; (p \; rpm) \tag{10.17}$$

$$P_e = 6{\times}10^{-4} \; D^2 L \; (p \; rpm)^2 \tag{10.18}$$

For the stator of an a-c machine, assuming a thickness of lamination of .36 mm, they are:

$$P_h = 2.3 \; D_o^2 L \; [.22 + .55p] \; rpm \tag{10.19}$$

$$P_e = 1.63{\times}10^{-4} \; D_o^2 L \; [.22 + .55p] \; (p \; rpm)^2 \tag{10.20}$$

The stray-load losses, by convention, are assumed to be 1% of the power input. An attempt is made here to separate the speed dependent component as follows:

$$P_{st.\ell.} = [6.5 \times 10^{-3} + 3.5 \times 10^{-3} \frac{rpm}{(rpm)_R}] P \qquad (10.21)$$

The windage losses are:

$$P_w = \frac{Qh}{.6} = .983 \times 10^{-4} (D\ rpm)^3_{blower} \frac{Q}{\sqrt{h}} \qquad (10.22)$$

where $Q = \frac{P_{loss}}{c\theta}$ = volumetric flow rate

h = head

c = 1200 = specific heat

θ = temperature rise.

11. Speed Reducing Transmission

The speed reducing transmission generally includes a differential, whose task is to allow relative motion of the drive wheels while cornering, and a reduction gear.

In this study the differential is assumed to be inserted in the transaxle housing, as is becoming standard practice, in order to save weight.

Reduction gears can have a fixed ratio, manual or automatic change, or be continuously variable. The ETV-1 and other electric vehicles employ fixed ratio chain drives, for which the claim is made that they are quieter than gears, highly efficient, and result in reduced transmission drag losses, because the side thrust associated with helical gears is eliminated[3]. Chain drives, however, are not suited for the 24,000 rpm a-c motor, because the peripheral speed would be too high. Moreover, the ground clearance requirements would impose a limit on the diameter of the sprocket on the differential. For this reason, only helical gears are considered.

The contemplated arrangement consists of motor and wheel drive having parallel axes and located in the front of the vehicle. In order to reduce the peripheral speed, the motor pinion is cut into the shaft and has 16 teeth. In the case of the a-c motors, the first mesh is enclosed in an aluminum housing which forms an integral part of the motor frame. Its gear ratio is 1:4, so that the speed is brought down to that of the fixed gear d-c motor. The remaining speed reduction is allocated to the differential. This facilitates the comparison between the two drives. When the drive includes a shifting transmission, it is inserted between the motor and the transaxle.

Estimates of the weight of the gear are based on the following considerations:

The ratio between the diameters of the pinion D_p and gear D_g is

$$\frac{D_p}{D_g} = \frac{Z_p}{Z_g} \qquad (11.1)$$

where Z stands for the number of teeth. It follows that, for equal width L_p, the ratio of their weights is

$$\frac{W_p}{W_g} = \frac{Z_p^2}{Z_g^2} \qquad (11.2)$$

Let t denote the tooth pitch

$$t = \frac{\pi D}{Z} \qquad (11.3)$$

and

$$\lambda = \frac{L_p}{t} \qquad (11.4)$$

then, the tooth pitch is related to the torque expressed in terms of $(\frac{kW}{rpm})$ as

$$t = 91 \sqrt[3]{\frac{1}{\sigma\lambda Z} \frac{kW}{rpm}} \qquad (11.5)$$

where σ = the allowable stress = $4.3\times10^9/(10+v)$. The weight of the pinion is then

$$W_p = \xi \frac{\pi}{4} D^2 L_p = \xi \frac{Z^2\lambda}{4\pi} t^3 = \xi \frac{7.53\times10^5 Z}{4\pi\sigma} \frac{kW}{(rpm)_p} \qquad (11.6)$$

where ξ = specific weight.

Introducing the appropriate values of ξ and σ, the weight of the mesh becomes

$$W_m = 8.3 \left(1 + \frac{Z_g^2}{Z_p^2}\right) Z_p \frac{kW}{(rpm)_p} \qquad (11.7)$$

To the weight of the meshes must be added the weight of the shafts, bearings, and housing.

The specific OEM cost is estimated at 2$/kg.

The most significant sources of loss are the gear mesh, gear windage, and support bearings. The gear mesh loss involves a sliding frictional component and a hydrodynamic component and the support bearing loss includes a load dependent and a viscous term. These losses have been the object of special NASA studies [16-17]. The following approximate fomula is based on these studies

$$P_{loss}/mesh = 1\times10^{-3} \left[2 + 2\frac{T}{T_R} + \left(\frac{rpm}{rpm_R}\right)^{1.8}\right] \frac{rpm}{rpm_R} P_R \qquad (11.8)$$

where the subscript R stands for rated. The first term in the square brackets accounts for the bearing and hydrodynamic component of the gear mesh loss. The second term accounts for the sliding frictional component of gear mesh loss and the third term for gear windage. A report by Garrett[18] groups the loss into a friction component, which is proportional to the power, and a churning and windage component which is proportional to the square of the speed. The ratio between the two components at rated load is given as 1:2.1.

Another Garrett report[4] gives curves for the transmission gear box efficiency which can be subsumed into the approximate formula

$$\eta_g = \frac{100}{1+.02\sqrt{T_R/T}} \qquad (11.9)$$

The gear considered is a 3-speed automatic transmission.

A very similar formula, having a coefficient of .018 instead of .02 in front of the square-root is given in a Rohr report[8] for the differential. In view of the fact that only one mesh contributes to the loss in the differential, the Garrett estimates seem to be on the high side. The Rohr report assigns an efficiency of .95 in low gear and .97 in high gear to the transmission.

12. Chosen Electric Drives

The direct approach to the design of the motors, as outlined, in Secs. 7, 8 and 9 was applied to optimize four specific types of electric drives. For the purpose of comparison, the drives were assumed to have the same constraints at the electrical and mechanical ports, i.e., the same battery voltage and the same speed at the input to the differential. The internal voltage and resistance of the battery were sources of uncertainty, because they vary with the type of battery, the load, and degree of discharge. In the design of the four drives, the battery was assumed to be an ideal voltage source with a constant voltage of 96V. The gear ratio of the differential was assumed to be the ratio dictated by the high-speed passing maneuver with a fixed gear. In the case of a d-c motor, mechanical stresses and considerations arising from the commutation problem limit the speed to about 6000 rpm. One then obtains according to Eq. (7.9)

$$r = \frac{6000}{1067} = 5.62. \qquad (12.1)$$

The limiting speed of the a-c motor was chosen as 24,000 rpm. The major limiting factor was considered noise. Also, in the case of the synchronous motor, which has a wound rotor, mechanical stresses could not be overlooked. In the case of the squirrel-cage motor a higher speed, and, therefore, a higher frequency would have necessitated the use of thinner and, therefore, more expensive laminations, in order to keep the core losses under control. Moreover, a higher frequency means a higher pulse frequency in the inverter with higher commutation losses.

The limiting values of the electric and magnetic loadings were chosen as

$$K = 7\times10^4 \text{ A/m} \quad \text{and} \quad B = .9\text{T} \tag{12.2}$$

for the d-c motors and

$$K = 10^5 \text{ A/m} \quad \text{and} \quad B = .65\text{T} \tag{12.3}$$

for the a-c motors.

As explained in Secs. 7, 8 and 9, the motor should be sized according to peak power demand, rather than the starting torque. Variability of the gear ratio by means of a shifting transmission reduces the starting torque requirement on the motor. For the reasons given in Sec. 8, however, the shifting transmission was considered only in connection with the d-c drive.

The major design features of the chosen electric drives are summarized below:

1. d-c motor with fixed gear (r = 5.62) and 6000 rpm maximum speed.

   $p = 2$, $D = .146$, $L = .14$, $g' = 2\times10^{-3}$

   $N = 36$, $Q = 24$.

   where Q = number of slots.

2. d-c motor with shifting transmission and 4000 rpm maximum speed.

   $p = 2$, $D = .12$, $L = .115$, $g' = 1.5\times10^{-3}$

   $N = 36$, $Q = 24$; $r = 9.49/6.73/5.02/3.75:1$

   (5.02:1 = direct; 3.75:1 = overdrive)

3. Synchronous motor with fixed gear ($r = 4\times5.62$) and 24000 rpm maximum speed.

$p = 1$, $D = .08$, $L = .1$, $g' = 5\times10^{-4}$

$m = 3$, $N = 12$, $Q = 36$.

4. Squirrel-cage motor with fixed gear ($r = 4\times5.62$) and 24000 rpm maximum speed.

   $p = 1$, $D = .08$, $L = .1$, $g' = 4\times10^{-4}$

   $m = 3$, $N = 12$, $Q_1 = 36$, $Q_2 = 46$

As explained in Sec. 4, the squirrel-cage motor needs a separate capacitive excitation, in order to provide regenerative braking. Because of the complexity of the arrangement, it was not considered here. For comparison purposes between the two a-c drives their stators were assumed to be identical.

13. Energy Balance in SAE Cycle

The energy requirements at the input to the differential are obtained by integrating Eqs. (3.8), (3.9) and (3.12), after the time dependence is introduced with the help of Eqs. (3.3) and (3.10). The following energy requirements at the wheels in kJ are then obtained:

acceleration	478	{ 369 kinetic energy 109 resistance
cruising	310	resistance
braking	-333	{ -369 kinetic energy 36 resistance

To the energy requirements at the wheels one must add the losses and subtract the energy recovered by regenerative braking. The resulting energy balances are given in Tables 13.1, 13.2 and 13.3 below.

Table 13.1 Energy Balance in kJ per Cycle
d-C Drive with Fixed Gear

		Mode of Operation				
		Acceleration	Cruise	Brake	Idle	
Road Load		478	310	(333)		
Losses	armature	38	4.7	12		
	field	20	7.9	8		
	core	4	11	3		
	friction	2.7	9.6	1.8		
	stray load	4	7.5	1		
	chopper	10				
	blower	.8	1.4	.6	.7	
	differential & axle	20	13	13		
Total Losses		99.5	55.1	39.4	.7	194.7
Gross consumption						943.3
Regeneration						(179.6)
Net consumption						763.7
Road load/consumption						1.03
Cycle efficiency*						.61

* cycle efficiency = $\frac{\text{Road Loss}}{\text{Net Consumption}}$

Table 13.2 Energy Balance in kJ per Cycle
d-c Drive with Shifting Transmission

		Mode of Operation				
		Acceleration	Cruise	Brake	Idle	
Road Load		478	310	(333)		
Losses	armature	38	4.7	12		
	field	16.6	6.6	6.6		
	core	1.5	5.3	.7		
	friction	1.3	4.8	.9		
	stray load	4	7.5	1		
	chopper	8				
	blower	.7	1.2	.5	.6	
	transmission	15	4	5		
	differential & axle	20	13	13		
Total Losses		105.1	47.1	39.7	.6	192.5
Gross consumption						940.8
Regeneration						(183.3)
Net consumption						757.5
Road load/consumption						1.04
Cycle efficiency*						.615

Table 13.3 Energy Balance in kJ per Cycle
Synchronous Drive

		Mode of Operation				
		Acceleration	Cruise	Brake	Idle	
Road Load		478	310	(333)		
Losses	armature	34	4	14		
	field	15	10	7		
	core	3.3	11.6	1.3		
	friction	3	10.5	2		
	stray load	4	7.5	1		
	inverter	22	28			
	rectifier			4		
	blower	.9	1.6	.6	.8	
	gear	7	4	2		
	differential & axle	20	13	13		
Total Losses		109.2	90.2	44.9	.8	245.1
Gross consumption						988.2
Regeneration						(180.1)
Net consumption						808.1
Road load/consumption						.975
Cycle efficiency*						.57

Table 13.4 Energy Balance in kJ per Cycle
Squirrel-Cage Drive

		Mode of Operation: Acceleration	Cruise	Brake	Idle	
Road Load		478	310	(333)		
Losses	copper	60	12			
	core	3.3	11.6			
	friction	3	10.5	2		
	stray load	3.3	7			
	inverter	24	30			
	blower	.8	1.5	.6	.8	
	gear	7	4	.8		
	differential & axle	20	13	13		
Total Losses		121.4	89.6	16.4	.8	228.2
Gross consumption						1003.2
Regeneration						
Net consumption						1003.2
Road load/consumption						.785
Cycle efficiency*						.464

14. Comparison of Weights and Costs

The breakdown of the minimum component weights and costs for the four drives is tabulated below.

Table 14.1 Breakdown of Weights and Costs

Drive Type	Component	Weight [kg]	OEM Cost [1976 $]
1. d-c with fixed gear	motor	110	770
	chopper	30	180
	by-pass contactor	2.5	10
		142.5	960
2. d-c with transmission	motor	60	420
	chopper	30	180
	by-pass contactor	2.5	10
	transmission	30	60
		122.5	670
3. Synchronous	motor	25	125
	inverter	75	525
	rectifier	35	210
	gear	5	10
		140	870
4. Squirrel cage	motor	21	89
	inverter	80	560
	gear	5	10
		106	659

15. Conclusions and Recommendations

Four propulsion systems have been selected and designed for optimal performance. The first system employs a d-c drive with fixed gear and its performance features are similar to those of the ETV-1. For this reason they will be chosen as basis for comparison. The second system also consists of a d-c drive, but with a shifting transmission. The third system employs a synchronous drive with fixed gear and a rectifier to allow for regenerative braking. The fourth system employs a squirrel-cage motor with fixed gear and no provisions for regeneration.

The criteria for the optimization of the overall propulsion system are:

- efficiency
- weight
- cost

The efficiency is computed for the performance of the SAE J227a Schedule D driving cycle and can be gleaned from the Tables of Section 14. It is defined as the ratio of the energy required to overcome the aerodynamic drag and tire rolling resistance, over the net energy with drawn from the battery. As seen from Table 15.1 the d-c drives have the best efficiency and the squirrel-cage motor the lowest. This is due to the inability of an induction motor to operate as a generator, unless it is provided with reactive power from a separate source. This source also determines the operating frequency. In an electric vehicle application, what is needed is, a complex power conditioner, a separate overexcited synchronous machine fed by the inverter or an adjustable resonant capacitor bank.

Table 15.1 Comparative Evaluation of Propulsion Systems in Per Units of Reference Systems

Quantity	1 (Reference) d-c fixed gear	2 d-c trans-mission	3 Syn-chronous fixed gear	4 Squirrel cage fixed gear
SAE cycle efficiency	1	1.008	.93	.76
SAE net energy consumption	1	.99	1.05	1.31
SAE range	1	1.014	.934	.68
weight	1	.85	.98	.74
cost	1	.69	.906	.686

In both cases the operating frequency must be controlled in a closed loop so as to maintain a prescribed value of negative slip. In view of these additional equipment requirements it was not deemed practical to operate the squirrel-cage motor in the regenerative mode.

More significant than the efficiency, is the net energy consumption which can be directly related to the range. To account for the effect of the discharge time on the average battery specific power density, the range was calculated by elevating the inverse of the per unit energy consumption to the 1.4 power. It must be realized, however, that this empirical factor is very sensitive to the type of battery employed.

With respect to range, the a-c drives are penalized by the need to have the power conditioner connected also under running condition and because the saturation voltage level is always below 100%. As a result, the currents and, therefore, the copper losses are higher than in the d-c drives. In addition the range of the squirrel-cage drive is reduced by almost one-third, because of lack of regeneration. For this reason the squirrel-cage drive can be competitive only in the case of vehicles used mainly in highway driving.

If the performance in highway driving were used as a criterion for the assessment of the drives, the efficiency of the d-c drive with transmission would be 3% higher than that of the d-c drive with fixed gear and the a-c drives would have an 8% lower efficiency.

With regard to the high-speed passing maneuver, if an upper limit of 500 A is set for the battery current, the d-c drives would develop 43kw, allowing an acceleration of .433 m/s^2 and resulting in an acceleration time from 88.5 km/h (55 mph) to 112.6 km/h (70 mph) of 15.5s. The corresponding accelerations and times would be 40kw and 36kw, .383 m/s^2 and .317 m/s^2, 17.31 s. and 20 s. for the synchronous and squirrel cage drive, respectively.

With regard to weight, the squirrel cage drives fare best, but the propulsion system accounts only for 6% of the gross weight of the vehicle and even in highway traffic the achievable 26% reduction in weight with respect to the d-c drives would result only in a 1% increase in range.

Finally with regard to cost, the a-c drives are penalized by the high costs of the power conditioners. The 31% saving in cost shown in Table 15.1 for the d-c drive with transmission would result in an 8% reduction in the overall cost of the vehicle. This saving, however, may not be fully realizable, because the introduction of the transmission in the propulsion system entails additional costs for procurement and manufacturing which were not taken into account.

In conclusion, the d-c drive with fixed gear seems very hard to beat at the present state of the art. Its main weakness is the need for frequent maintenance. Brushless, synchronous drives represent the most promising alternative and should constitute the main area for future development. Moreover the power conditioner, whether chopper or inverter, is much in need of improvement. Particular effort should be devoted to increase the saturation voltage level and to decrease its cost and weight.

References

1. NAPCA Vehicle Design Goal V_{max} = 70 MPH Level Grade.
2. J. Walker, Private Communication.
3. Near-Term Electric Vehicle, Phase II - Final Report, General Electric Company, March 18, 1980.
4. Study of Heat Engine/Flywheel Phase I Final Report ALO-41/1 UC-96 Garrett-AiResearch, April 1978.
5. Near-Term Electric Vehicle, Phase II Mid-term Summary Report, General Electric Company, July 1, 1978.
6. Economic and Technical Feasibility Study for Energy Storage Flywheels ERDA 76-65, December 1975.
7. State-of-the-Art Assessment of Electric and Hybrid Vehicles, CONS/1011-1 NASA TM-73756, September 1977.
8. Preliminary Power Train Design for a State-of-the-Art Electric Vehicle DOE/NASA/0592-78/1 NASA CR-135340 RHR-78-035, April 1978.
9. Preliminary Power Train Design for a State-of-the-Art Electric Vehicle DOE/NASA/0595-78/1 NASA CR-135341, April 1978.
10. E. Levi, Brushless Electrical Machine with Hybrid Excitation. U.S. Patent Application No. 06/125,563.
11. E. Levi and M. Panzer, Electromechanical Power Conversion, Dover Publications, Inc., New YOrk, 1974.
12. Electric Car Design, Interim Summary Report Phase I, General Electric Company, May 4, 1977.
13. L. Greenwood, Design of Direct Current Machines, MacDonald & Co. Ltd., London, 1949.
14. M. Liwschitz-Garik and Clyde C. Whipple, A-C Machines, D. Van Nostrand Co., Inc., Princeton 1961.
15. Steel Products Manual, Flat Rolled Electrical Steel AISI, Washington, D.C., 1975.
16. Spur-Gear-System Efficiency at Part and Full Load, NASA Technical Paper 1622/AVRADCOM Technical Report 79-46, February 1980.
17. Friction Losses in Lubricated Thrust-Loaded Gageless Angular-Contact Bearing NASA TN D-7356, July 1973.

18. E. F. Echolds and P. S. Walia, Lightweight Electronically Commutated dc Motor for Electric Passenger Vehicles. Airesearch Manufacturing Company, DOE/NASA/0064-1, NASA CR-165601, Airesearch 81-18266, September 1982.

PERFORMANCE STANDARDS

SUMMARY

Public Law 94-413, Section 7, as amended, calls for DOE to establish performance standards that specify the minimum criteria for the Demonstration Project. The first standards were published in the *Federal Register* on May 30, 1978. The standards will be revised periodically as the electric and hybrid vehicle (EHV) state of the art improves. For the current standards refer to the *Federal Register*, Volume 45, Number 30, page 9542, February 12, 1980. The test conditions and procedures for determining levels of performance are stated in SAE J227a.

DEFINITIONS

Electric Vehicle: A vehicle that depends solely upon an energy source of externally generated electricity. The energy is stored aboard the vehicle in an energy storage device, such as a secondary battery.

Hybrid Vehicle (HV): A vehicle that is fueled from more than one external source of energy, one source being electricity; for example, a vehicle that has both an onboard gasoline tank supplying a heat engine and batteries recharged from an offboard source of electricity. A majority of propulsion energy must be supplied by the external electric source.

Personal-Use Vehicle: A vehicle designed and used primarily for transporting the vehicle operator and up to nine passengers.

Commercial Vehicle: A vehicle other than a personal-use vehicle.

STANDARDS AS OF March 13, 1980

Parameter	Personal use	Commercial use
Forward speed capability	80 km/h for 5 min	75 km/h for 5 min
Range	55 km (EV) and 200 km (HV) on SAE J227a/C cycle	60 km (EV) and 200 km (HV) on SAE J227a/B cycle
Acceleration	0 to 50 km/h in 13.5 s	0 to 50 km/h in 14 s
Gradeability limit	20% grade for 20 s, either backward or forward	20% grade for 20 s, either backward or forward
Gradeability at speed	25 km/h on 10% grade	25 km/h on 10% grade
Battery recharge time	10 h from 80% discharge	10 h from 80% discharge
Battery life	75% of specified range after 12 months or 15,000 km; 100% of specified acceleration and gradeability	75% of specified range after 12 months or 15,000 km; 100% of specified acceleration and gradeability
Emissions, safety, and crashworthiness	Federal Motor Vehicle Safety Standards and other safety standards appropriate to EHV's	Federal Motor Vehicle Safety Standards and other safety standards appropriate to EHV's

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15. Supplementary Notes

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16. Abstract

This study compares the efficiency, weight, and cost of various propulsion systems for 4-passenger electric vehicles. These systems comprise the electric motor and the required speed reducing transmission to obtain the appropriate speed at the wheel. Three types of motors, dc synchronous, and squirrel-cage were considered at 6000 ycm and 24 000 rpm for a peak power of 40 kW. Two types of gearing selected were a single speed differential and a differential with a differential with a 4-speed gearbox. Only components that were readily realizable within present state-of-the-art were considered.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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