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Theoretical Prediction of Electric Vehicle Energy Consumption and Battery State-of-Charge During Arbitrary Driving Cycles

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ABSTRACT

In order to obtain a reliable comparison of electric vehicle propulsion systems in an early state of development, a digital computer simulation program has been developed.
Starting with the road-load the power flow through the entire drive line is calculated for a specified driving cycle, including regenerative braking. The energy-efficiency characteristics of motor and transmission are taken in account as a function of both torque and speed. Experimentally obtained component characteristics are used to define the drive line. In the program a battery state-of-charge model for the lead-acid battery is implied, which is based on the non-linear ampere-hour capacity versus normalized constant discharge curve. As the vehicle proceeds on the chosen driving cycle cumulative charge reduction is determined. Battery voltage is modeled as a function of battery current and depth of discharge. Results for different drive trains are discussed. It is shown that the energy use of a propulsion train with a variable transmission ratio is lower than that of a drive system with a fixed gear ratio. It appears that this simulation gives a good insight in the energy use and losses of the various parts of the drive train.

1. INTRODUCTION

Many motor-car manufacturers are developing and testing several power train systems in various electric vehicles. Due to different vehicle characteristics and testing conditions it is nearly impossible to obtain a reliable comparison of these drive trains. For this reason a multi-disciplinary working group at the Eindhoven University of Technology has set out to construct and test various drive systems in the same vehicle and under identical conditions.

In order to optimize the operating range and the consumption of primary energy, the components of the drive system have to be matched. Specifically this matching of components is important if regenerative braking is considered, since the braking power has to pass along the drive train twice.

It is difficult to dertermine the influence of different drive train systems on the vehicle energy use and the operating range because:

- the efficiencies of the component parts of a power train system are not constant, but can vary strongly for each operating point (torque and speed) of the relevant component.
- even during standard duty cycles the wheel-power requirements - and consequently the component efficiencies - are seldom reproducible.
- the total amount of energy which can be delivered by the battery depends on the present and past rates of discharge and/or charge.

Therefore a detailed vehicle simulation program has been developed in order to compare and match different drive trains. Within the program several mathematical models for battery, chopper, motor, gearbox, torque converter and vehicle can be stored in the form of both tables and equations. The technique of assembling a drive train and a vehicle from models, in which the measured and/or estimated efficiencies are computable for each operating point, makes the program extremely flexible and new models can be created and added at any time. The drive train model can be applied to simulate the energy use of an electric vehicle during a specified test cycle. Examples of interesting output variables are: battery voltage, current and state-of-charge, distance covered, average gearbox efficiency and average motor efficiency.

Computer simulation of the power train system with respect to energy economy offers the following benifits:

- reproducibility of results; no influences beyond control as weather conditions
- fast response time; evaluation of alternatives is possible in a short period of time
- evaluation of component changes is possible before and during vehicle development; consequent savings in expenditures.

In this paper the vehicle simulation model will be described for a given electric vehicle drive system.

2. VEHICLE MODEL

In order to obtain reliable simulation results an accurate analysis of the vehicle resistance is indispensable. The vehicle road-load is the sum of aerodynamic resistance, rolling resistance and grade resistance.

The air resistance of the vehicle can be expressed as

$$F_w = \tfrac{1}{2}\,\rho * V_{res}^2 * A_F * C_w \qquad (1)$$

where

F_w	aerodynamic resistance	(N)
ρ	specific air density	(kg/m^3)
V_{res}	relative vehicle speed with respect to the air	(m/s)
A_F	frontal surface area of the vehicle	(m^2)
C_w	aerodynamic drag coefficient	(-)

The drag coefficient is dependent on the shape of the vehicle only and varies between 0.30 for well streamlined motor-cars and 0.55 for ill streamlined passenger cars.

The rolling resistance of the vehicle is given by

$$F_r = f_r * F_N \qquad (2)$$

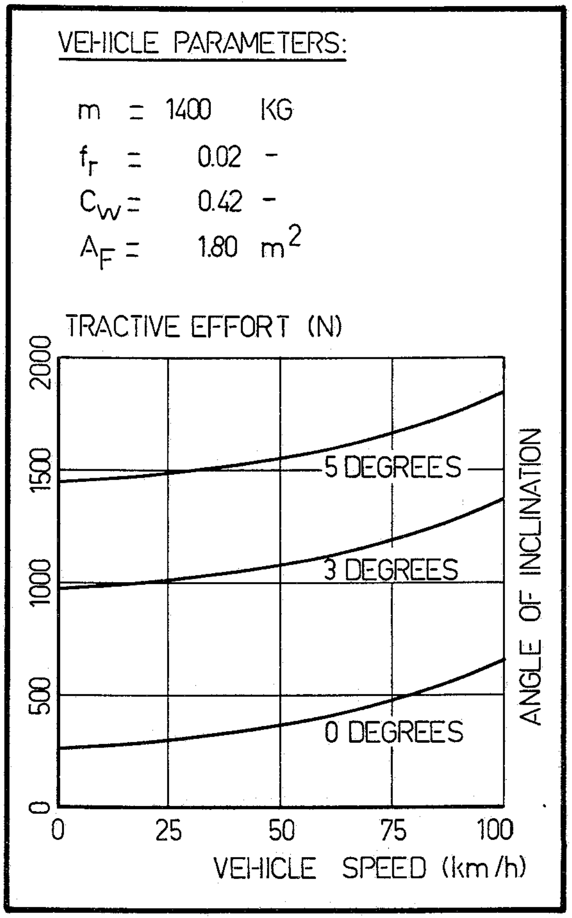

Figure 1. Constant speed tractive effort.

where

F_r	rolling resistance	(N)
f_r	rolling resistance factor of the wheels	(-)
F_N	load on the wheels perpendicular to the road surface	(N)

Concerning the rolling resistance factor the development of radial-ply tyres has paid dividends. In this work the use of tyres with a rolling resistance coefficient of 0.02 was assumed and variations due to effects as tyre warming up are considered small and neglected. The value of F_N depends on the character of the road; if a motor-car climbs a gradient, $m * g * \cos\alpha$ is that part of the vehicle weight which determines the wheel pressure on the road surface, so that the rolling resistance on gradients is always lower then on level roads.

The hill-climbing resistance is given by:

$$F_h = m * g * \sin \alpha \qquad (3)$$

where

F_h	hill-climbing resistance	(N)
m	total vehicle mass	(kg)
g	gravitational acceleration	(m/s^2)
α	inclination angle	(-)

The dynamic part of the car resistance is determined by the force which is necessary to accelerate the vehicle. Resistance is experienced in accelerating the total vehicle mass in a translational sense and in accelerating the rotating parts.

The acceleration resistance may be calculated as:

$$F_a = \left[m + \Sigma \left(\frac{i}{r}\right)^2 \right] \frac{dv}{dt} \qquad (4)$$

where

F_a	resistance due to acceleration	(N)
$\Sigma I \left(\frac{i}{r}\right)^2$	the moments of inertia (I) referenced to the circumference of the driving wheel	(kg)
i	gearbox ratio	(-)
r	wheel radius	(m)

Often the sum of moments of inertia is taken in consideration with a mass factor, λ, which depends on the engaged gear, so that the momentary acceleration resistance (F_a) can be determined from the following differential equation:

$$F_a = \lambda * m * \frac{dv}{dt} \qquad (5)$$

where

λ	mass factor (1.06-1.34)	(-)

Now the total car resistance can be determined as

$$F_{tot} = \tfrac{1}{2}\rho * V_{res}^2 * A_F * C_w + m \left[g * f_r * \cos \alpha + g * \sin \alpha + \lambda * \frac{dv}{dt} \right] \qquad (6)$$

During an arbitrary driving cycle, the total energy requirement of the vehicle (W) can be determined by the following expression, if a constant drive train efficiency η is assumed in first instance:

$$W = \frac{1}{\eta} \int_0^{t_{end}} \left[F_{tot} * v \right] dt \qquad (7)$$

3. BATTERY MODEL

The battery is not only the most important part of the electric vehicle, but often the least reliable component. This is due to the fact that the amount of energy which the battery can deliver is determined by its state-of-charge. The battery state-of-charge depends upon the discharge and charge history of this energy source. During the vehicle run the state-of-charge decreases until finally the power requirements of the drive train can no longer be met. The state-of-charge is thus a crucial parameter in the calculation of the performance.

The state of a fully charged battery is well defined; however the state of a fully discharged battery depends on the discharge current: the higher the current, the lower is the available capacity. This is expressed in the empirical Peuckert relation, which states that for any current I the product

$$I^n * \tau = \text{constant} \qquad (8)$$

where

τ = time required for total discharge at current I

n = number, depending on the battery type; usually $n \approx 1.3$.

Defining C_N as the capacity at standard discharge rate (I_N) and with $C_I = I * \tau$, equation (8) can be written as

$$C_I = C_N * \left(\frac{I_N}{I}\right)^{n-1} \qquad (9)$$

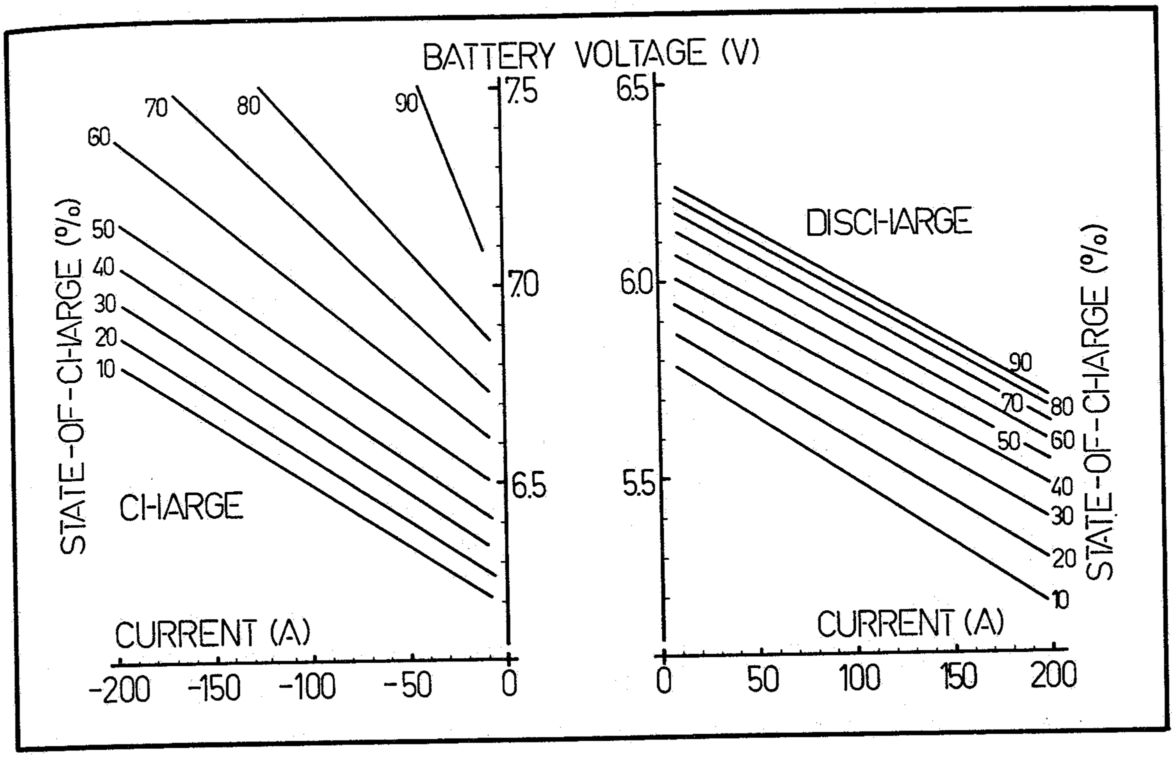

Figure 2. Voltage-current characteristics.

For electric car batteries the capacity at the 5 hr rate (C_5) is usually taken for C_N.
During discharge with current I, the state-of-charge (S) at time t can be given as [2]

$$S = 1 - \frac{I \ast t}{C_I} \qquad (10)$$

or with substitution of equation (9):

$$S = 1 - \frac{I \ast t}{C_N} \left(\frac{I}{I_N}\right)^{n-1} \qquad (11)$$

When the discharge occurs according to a duty cycle the current follows a rapidly varying pattern. The state-of-charge is then calculated for small time intervals Δt, during which I is considered to be constant:

$$S = 1 - \frac{I \ast \Delta t}{C_N} \left(\frac{I}{I_N}\right)^{n-1} \qquad (11a)$$

If also regenerative braking is involved in the duty cycle, then its effect on the state-of-charge must be accounted for. The incremental change of state-of-charge due to recharge with current I_c during a period Δt_c is related to the previous extent of discharge

$$\Delta S = \frac{I_c \ast \Delta t_c}{C_{I,d}} \qquad (12)$$

(subscripts c en d refer to charge and discharge).
With equations (9) en (11a) this can be transformed into

$$\Delta S = \frac{I_c \ast \Delta t_c}{I_d \ast \Delta t_d} (1 - S) \qquad (13)$$

When equation (13) is to be used in the case of complete recharging of a battery, a charge efficiency factor must be included because of the occurence of the water electrolysis, which becomes concurrent with the charging process during the final charging. The extent of the gassing depends on the state-of-charge and the charging current and is the predominant process for cell voltage > 2.35 Volts. For the complete recharging of a fully discharged battery the average charge efficiency factor is about 0.90.

In order to obtain more information about the charging efficiency during duty cycle operation, charge efficiency measurements were carried out for duty cycles with and without regenerative braking. The duty cycle, which was applied, is an actual duty cycle as described earlier [3]. In these experiments the duration of the duty cycle was varied from 20 minutes (decrease of S is 6%) to 180 minutes. From the results it can be concluded that the partial recharge during a duty cycle occurs with 100% efficiency. Whether this also holds for a nearly full battery $0.94 \leqslant S \leqslant 1$ was not established, but the values of the cell voltage for recharge pulses during the initial part of the duty cycle generally do not exceed the gassing voltage even though the current during recharge can reach values of $5 * I_5$.

Experimental data of battery voltage as a function of the state-of-charge were collected from discharge and charge measurements at a 6 Volts battery (C_5 = 180 Ah).

From the voltage-time recordings at constant I (I was varied from I_5 to $5 * I_5$) voltage-current plots were constructed at constant S, as shown in Figure 2. Since the charge efficiency is not known the data in the charge plot for $E > 7.25$ Volts can only be indicative and refer actually to lower S.

4. MOTOR MODEL

The purpose of the motor model is to describe the motor efficiency as a function of the motor shaft output torque and speed over the entire operating range. The DC motor is actually a converter between the electrical power source and the mechanical drive train.

Several models for DC motors can be stored in the program; in this paper the model of a separately excited DC motor is discussed.

The armature controller adjusts the voltage applied to the armature of this motor and a field controller performs the same function with respect to the field.

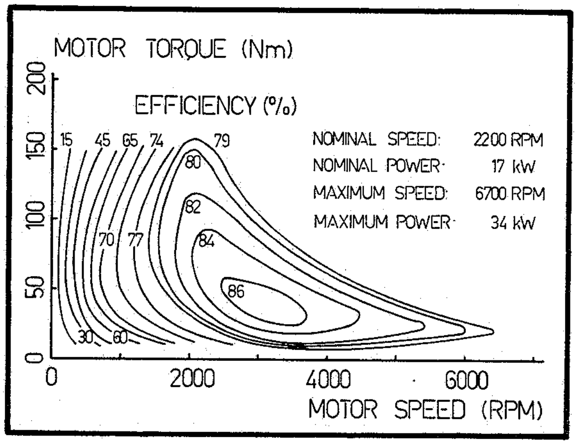

Figure 3. Motor efficiency.

For low rotation speeds of the motor the field current is kept constant and the speed is adjusted by controlling the armature voltage. With increasing rotation speed finally the full battery voltage is applied to the motor and further increase of speed is then realised by reduction of the field current. In this case the armature chopper can be bypassed which consequently results in a controller efficiency close to 100%.

The motor type is specified by

- peak power rating during three minutes
- continuous power rating
- maximum speed
- nominal speed, below which the motor operates in constant torque and above the motor operates in constant power (in connection with eventual short-circuiting of the chopper - and thus eliminating power losses in it - at speeds exceeding this number of revolutions).

The motor efficiency model is generated by using the manufacturers test data which we verified for speeds up to 3000 RPM. These motor data (Figure 3) might be stored as an efficiency table, so that the efficiency can be obtained by interpolation. This technique has not been used because of the large memory space required for a high accuracy. The motor efficiencies are represented by equations, which have been obtained by surface fitting in the form of bicubic splines.

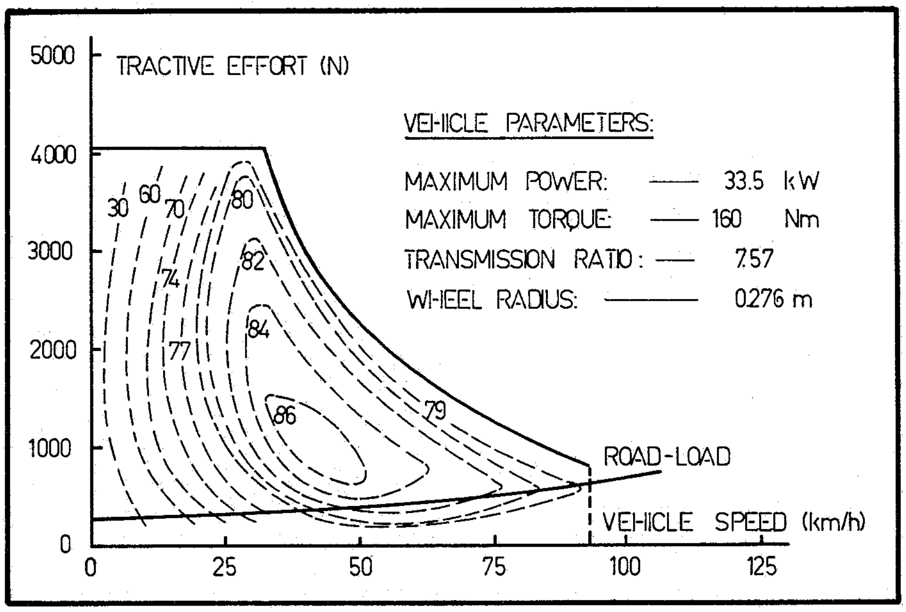

Figure 4. Vehicle characteristics; fixed gear ratio.

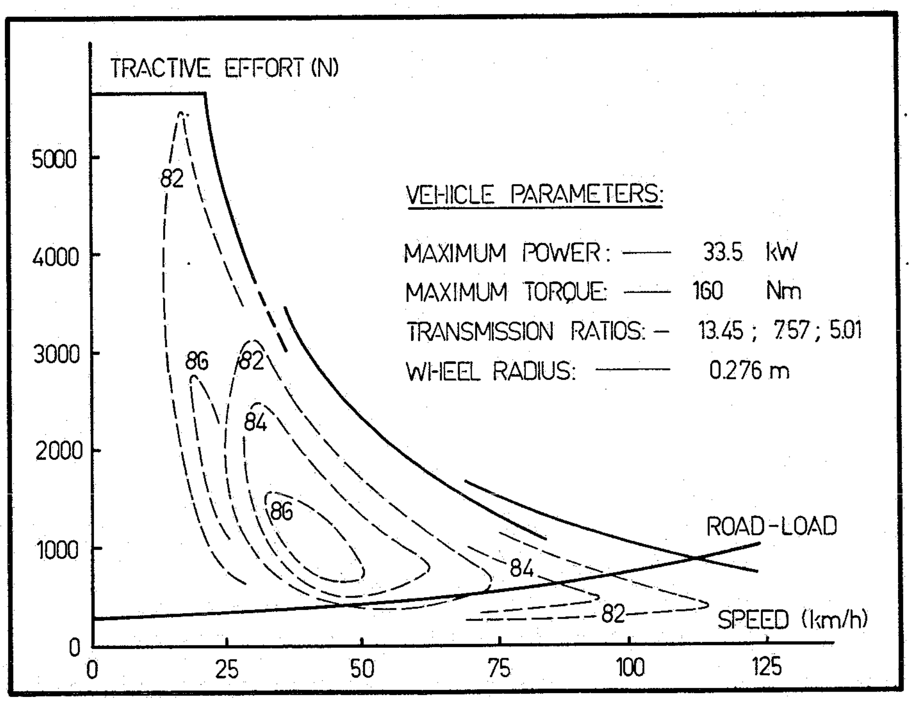

Figure 5. Vehicle characteristics; variable gear ratio.

For reasons of simplicity the same set of efficiency data is used when the machine is operating as a generator. Motor efficiency is then calculated as a function of the required output performance, which results from the driving cycle.

5. MECHANICAL TRANSMISSION

In principle a vehicle requires an infinite speed control range, because all speeds between standstill and maximum speed must be attainable. However speeds between 0 and 5 to 10 km/h are of short duration, so that a 20 : 1 control range at high efficiency is sufficient. Owing to the relatively low current requirements of seperately excited fields, field controllers are almost exclusively cheap single-quadrant transistor type controllers. Because only a 3 : 1 control range is realised by field weakening, further adjustment is necessary by variation of the armature voltage and/or variable transmission ratios.

If the separately excited motor is controlled continuously by an armature chopper and a field controller, every point within the torque-speed envelope can be adjusted and an infinite control range is realised; consequently a fixed gear ratio is sufficient (Figure 4). Because separately excited motors are less efficient at low speeds, a manual or automatic gear drive may be attractive, because these gears allow highly efficient motor operation. Figure 5 shows the propulsion characteristics of the motor in combination with 3 speeds of a manual gearbox. Another advantage of this propulsion system is that in this case the armature controller is not required. However the disadvantages of this system are reduced driving comfort and operatibility: a fully electronic system permits completely yerk-free acceleration and driving without gear change. It may be noticed that the behaviour of the former propulsion system is exactly the same as that of an ICE-vehicle with a normal gearbox.

Usually motor-car manufacturers assume a fixed gearbox efficiency (95 to 97%). In case of propulsion by internal combustion engines the gearbox efficiency is of small importance, because transmission losses are small in comparison with ICE losses, although even this statement is disputable. With respect to the relatively small amount of stored energy in the electric car particular attention has to be paid to losses in the electric vehicle gears. The losses in these components are functions of both speed and load again. The total loss of power is due to two main causes; (i), the viscous resistance due to gear-wheel churning in the lubricant and friction in bearings and seals and, (ii), the friction between the sliding teeth of the gears. The former is independent of and the latter dependent on the load transmitted, The tooth friction is practically unaffected by changes of speed.

From efficiency measurements at the Eindhoven University curves at constant efficiency have been constructed for a 4-speed manual transmission, including differential, as it is used in the european VW Rabbit 1600 (Figure 6). The measured efficiencies are relatively high because a helical gear type final drive has been integrated with the transmission instead of the usually seperate bevel gear final reduction. In the simulation model these efficiency characteristics are represented by equations, using surface fitting with bicubic splines. Increases in efficiency due to effects as gear lubricant warming up were considered small and therefore neglected. It is planned to extend the program by a model for an automatic 3-speed planetary gearbox by the end of this year.

6. ELECTRIC VEHICLE SIMULATION

The principle of a drive train simulation is to calculate the power-flow through this train during a specified duty cyle in which the vehicle speed has been

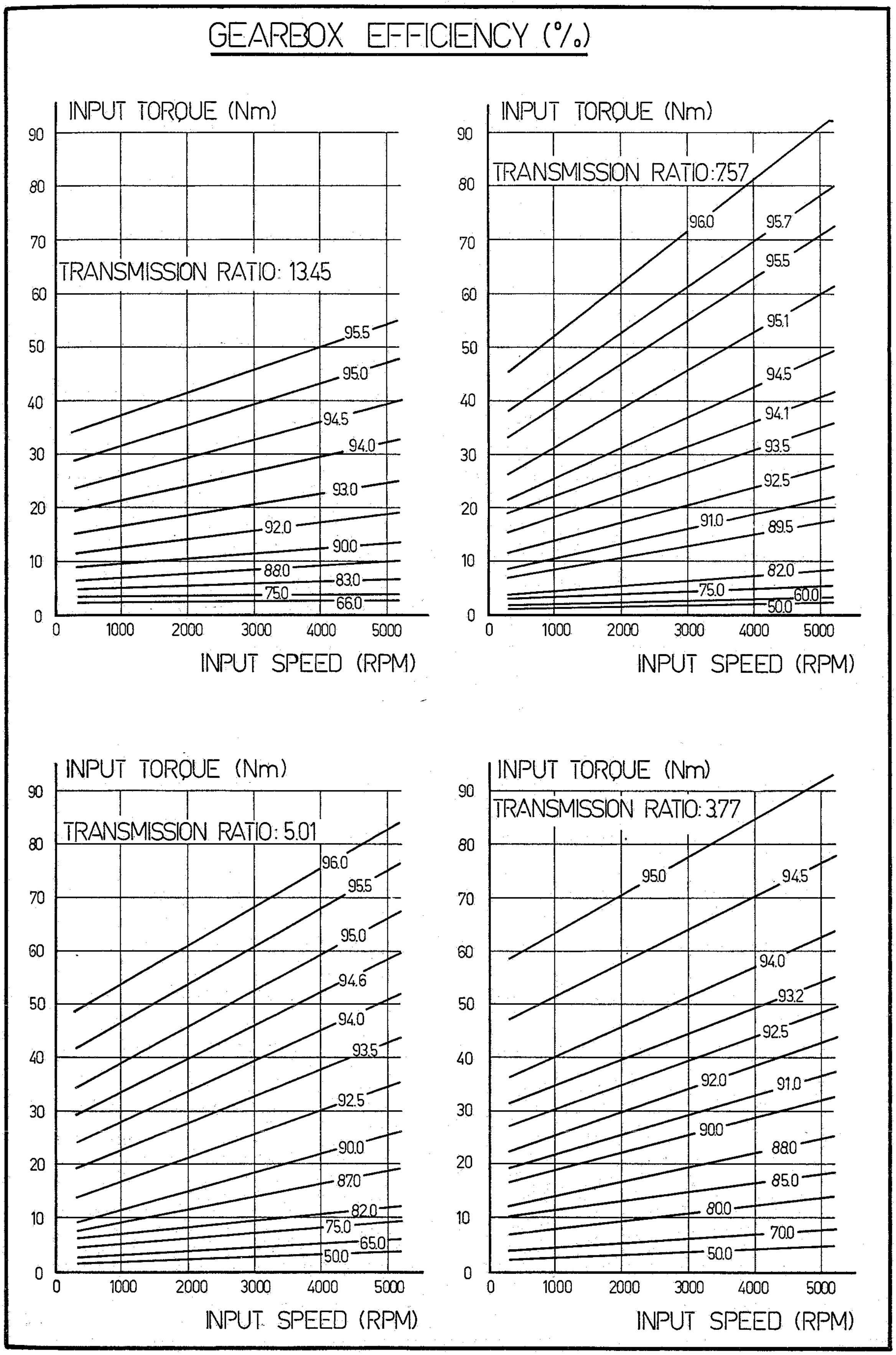

Figure 6. Gearbox efficiency.

prescribed as a function of time. Starting with the wheel power requirements the power flow is calculated from the wheels through the gears, motor and electronic controllers to the battery for a sequence of speeds constituting the total driving cycle. Regenerative braking has been included.

The input variables of the computer program by which the simulation is carried out comprise the characteristics of vehicle, transmission, motor, controller, battery and driving cycle and have been listed in Table 1. The flow-chart, given in Figure 7, represents the sequential and logical structure of the program.

From the characteristics of motor, transmission and battery, as discussed in previous chapters, the conditions and each operating point can be calculated by means of subroutines.

It has been assumed that the battery can deliver the required power until a determined minimum cell voltage is reached where the battery is declared to be fully discharged. In the same way regenerative braking is not permitted above a maximum charging voltage, related with "gassing" voltage. In this case the battery may only be charged by a current, which is allowed by this voltage and the power remainder is assumed to be dissipated in the mechanical brakes.

The output of the simulation provides numerical values for e.g.: instanteous tractive effort, conditions of transmission, motor and battery and cumulative energy used and distance covered. These are shown in Figures 8 and 9.

If during motoring or regenerative braking a drive situation requires a motor speed and/or torque exceeding the limits of the motor data, the program excecution terminates. The program has been built up in a modular way, so that it can easily be adapted for other types of components and/or drive lines.

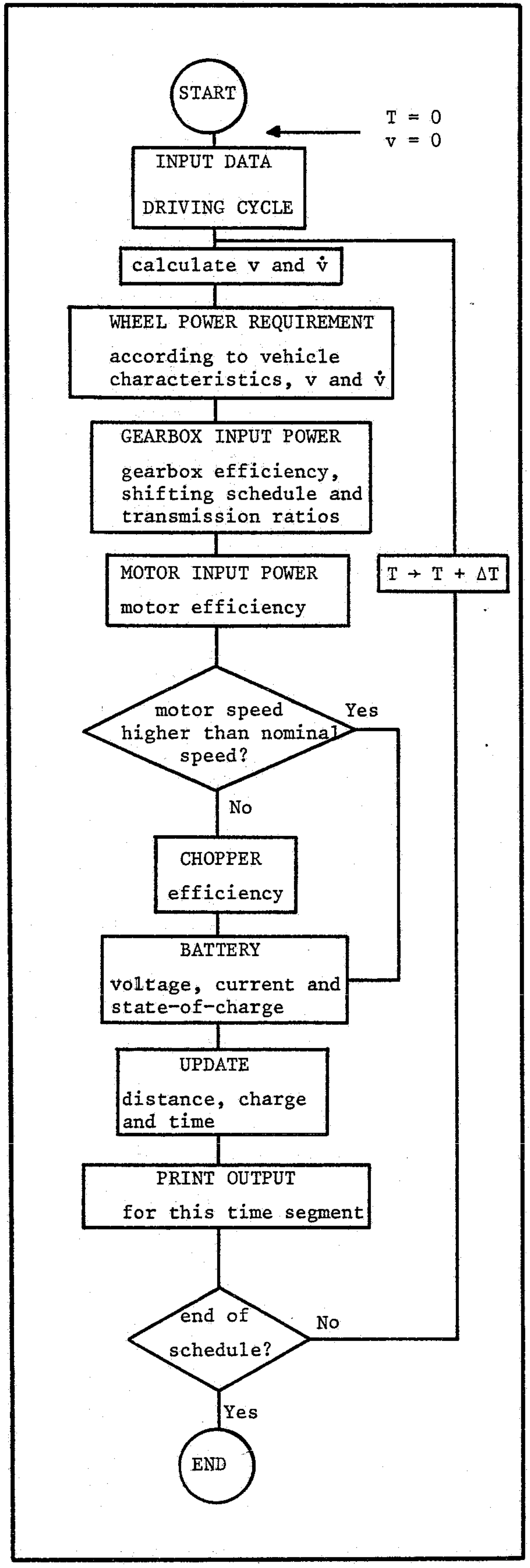

Figure 7. Simulation flow-chart.

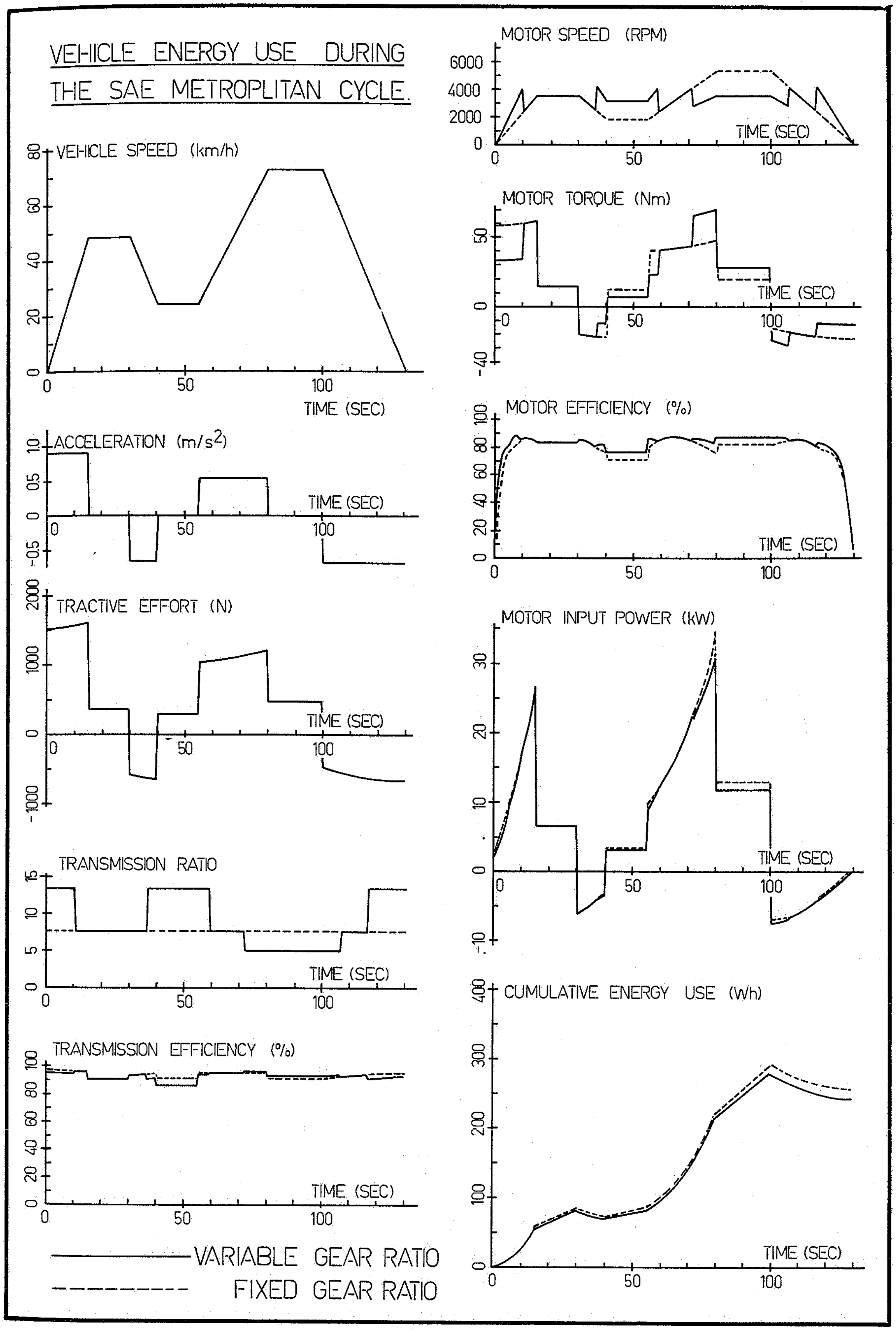

Figure 8. Vehicle energy use on driving cycle.

VEHICLE	MOTOR	BATTERY
. weight . frontal area surface . aerodynamic drag coefficient . rolling resistance coefficient . wheel radius	. maximum power . nominal power . maximum speed . nominal speed . efficiency map	. discharge capacity at 5 hour rate . nominal voltage . maximum voltage . minimum voltage . voltage characteristics as function of current and state-of-charge . charge efficiency
TRANSMISSION	CONTROLLER	DRIVING CYCLE
. efficiency maps . transmission ratios . shifting schedule	. efficiency	. arrays of velocity-time pairs . time step Δt

Table 1. Input parameters for EV simulation.

7. RESULTS AND CONCLUSIONS

The described computer simulation has been applied to an electric vehicle following the SAE J227 Metropolitan Cycle. Although other cycles can easily be used this cycle has been chosen because it concerns a short driving schedule with variety of speeds. The test vehicle is a completely modified Volkswagen Rabbit, equipped with a separately excited DC motor and a fully electronic motor control, which allows regenerative braking. The complete specifications are given in Table 2.

The battery pack consists of 24 lead-acid batteries of 6 Volts each. The end of the operating range was declared to be reached when the battery is unable to meet the power demand at any value of battery voltage above the minimum, which has been fixed at 120 Volts. In connection with gassing the maximum battery pack voltage has been specified at 174 Volts. For applying these criteria accurate simulation of the battery voltage, including cumulative battery charge reduction is of vital importance over the entire operating range.

Figure 8 shows interesting output variables of the vehicle - using a manual gearbox and a fixed gear ratio - for the Metropolitan Cycle.

In order to obtain an as efficient as possible motor operating the shifting schedule is defined in such a manner that motor speeds are kept between 2500 and 4000 RPM. This highly efficient motor operation results in a low cumulative energy use.

vehicle weight	1400.00 kg
rolling resistance coefficient	0.02 -
frontal surface area	1.80 m^2
aerdodynamic drag coefficient	0.42 -
wheel radius	0.276 m
max. motor output power	33.50 kW
max. motor output torque	160.00 Nm
battery pack:	
. nominal voltage	144.00 V
. nominal capacity at 5-hour rate	180.00 Ah
motor efficiency according to Figure 3	
transmission efficiency according to Figure 6.	

Table 2. Vehicle specifications.

In the course of the battery discharge the voltage required to provide a certain power decreases and consequently the current increases.

Energy use of SAE Metropolitan Cycle	PROPULSION TRAIN			
	1. 3-speed manual gearbox	2. fixed gear ratio: 7.57	3. fixed gear ratio: 5.01	4. fixed gear ratio: 3.77
motor speed (RPM)	2500-4000 90% of time	0-5300	0-3500	0-2600
energy requirement at motor terminals (Wh/tkm)	112.4	119.2	118.2	128.4
av. motor efficiency (%)	80.70	77.88	76.67	73.56
av. transmission efficiency (%)	92.54	93.08	94.52	93.99
av. drive train efficiency (%)	74.68	72.49	72.47	69.14
max. motor input power (kW)	31.0	34.5	31.0	30.8
max. motor output torque (Nm)	70.0	61.4	91.9	123.6
operating range (km)	85.6	73.3	81.0	74.8
discharged ampere-hours	101.94	92.21	101.66	101.50
average current (A)	50.7	53.6	53.5	57.8

Table 3. Simulation results;different propulsion trains.

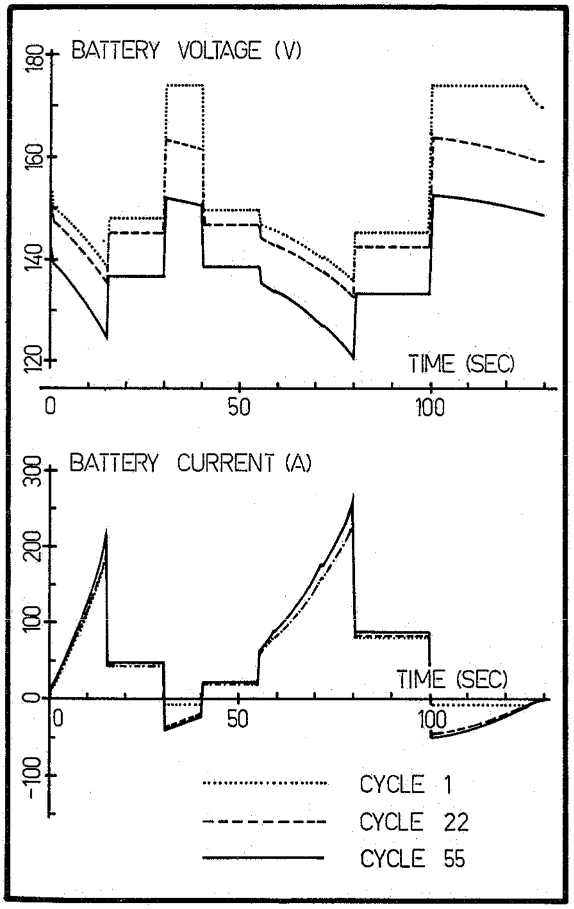

Figure 9. Battery voltage and current on SAE Metropolitan Cycle.

Battery voltage and current obtained by simulation of the first, twenty-second and fifty-fifth cycle of the vehicle with a variable gear ratio are shown in Figure 9. At the end of the second acceleration period, where the required power reaches a maximum value, the battery voltages are 135, 132 and 120.5 Volts respectively.

Table 3 shows the comparison of these drive trains with two alternative trains using a fixed gear ratio. Propulsion train 4 uses an extremely low transmission ratio, resulting in a poor motor efficiency. That is precisely the reason why the energy requirement at the motor terminals is relatively high. The average drive train efficiencies of alternatives 2 and 3 stand at 72.5% both, with consequently approximately equal motor input energy requirements. However the peak power requirement of propulsion train 2 is relatively high because a lower instantaneous drive train efficiency coincides with the maximum wheel power requirement.

Because of this higher peak power the specified minimum battery voltage is reached sooner, which results in a smaller operating range.

It may be concluded that:

- from an energetical point of view a propulsion train using a variable transmisson ratio has to be preferred to a drive system with a fixed gear ratio.
- the operating range depends on both peak power requirement and average energy requirement per kilometer; so power train optimizing with respect to the peak power demand is strongly recommended.
- this simulation program allows an accurate comparison of vehicle drive trains while component deficiencies are obviously demonstrated.

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