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5030-574
Electric and Hybrid Vehicle
System Research and Development Project

DOE/CS-54209-23
Distribution Category UC-96

(NASA-CR-175652) A SYSTEM-LEVEL MATHEMATICAL MODEL FOR EVALUATION OF POWER TRAIN PERFORMANCE OF LOAD-LEVELED ELECTRIC-VEHICLES (Jet Propulsion Lab.) 37 p HC A03/MF A01 CSCL 13F G3/85

N85-25009

Unclas 14812

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This publication reports on work done under NASA Task RE-152, Amendment 170, DOE/NASA IAA DE-AI01-78CS54209.

ABSTRACT

The power train performance of load-leveled electric vehicles can be compared with that of non-load-leveled systems by use of a simple mathematical model. This method of measurement involves a number of parameters including the degree of load leveling and regeneration, the flywheel mechanical-to-electrical energy fraction, and efficiencies of the motor, generator, flywheel, and transmission. Basic efficiency terms are defined and representative comparisons of a variety of systems are presented.

Results of the study indicate that mechanical transfer of energy into and out of the flywheel is more advantageous than electrical transfer. An optimum degree of load leveling may be achieved in terms of the driving cycle, battery characteristics, mode of mechanization, and the efficiency of the components. For state-of-the-art mechanically coupled flywheel systems, load-leveling losses can be held to a reasonable 10%; electrically coupled systems can have losses that are up to six times larger. Propulsion system efficiencies for mechanically coupled flywheel systems are predicted to be approximately the 60% achieved on conventional non-load-leveled systems.

NOMENCLATURE

E_{AERO}	energy going into aerodynamic drag
E_{BAT}	original energy supplied at battery terminals
E_{BR}	energy going into brakes (energy required for acceleration)
E_{RF}	regenerated energy stored in the flywheel
E_{RR}	energy going into rolling resistance
e_{AERO}	specific energy going into aerodynamic drag (energy per unit distance)
e_{BR}	specific energy going into brakes, or that required for acceleration (energy per unit distance)
e_{RR}	specific energy going into rolling resistance (energy per unit distance)
f	degree of regeneration
F_{ℓ}	gross speed-related flywheel parasitic losses as a fraction of original battery energy
R	vehicle range of non-regenerative system; also range in general
R_{REG}	vehicle range of regenerative system
x	fraction of original battery energy passing through the motor
$(1-x)$	degree of load leveling
y	flywheel electrical energy fraction
$(1-y)$	flywheel mechanical energy fraction
z	flywheel electrical fraction of regeneration
$(1-z)$	flywheel mechanical fraction of regeneration
η_{bc}	battery charge efficiency
η_{bcd}	battery charge-discharge efficiency (equals $\eta_{bc} \times \eta_{bd}$)
η_{bd}	battery discharge efficiency
η_{ft}	efficiency of transmission between flywheel and rear axle
η_{g}	generator efficiency
η_{gt}	efficiency of transmission between generator and flywheel

η_m motor efficiency

η_{mt} efficiency of transmission between motor and rear axle

η_{PT} power train efficiency

η_{REG} regeneration efficiency

η_{SYS} propulsion system efficiency of non-regenerative system; also propulsion system efficiency in general

$\eta_{SYS-REG}$ propulsion system efficiency of regenerated system

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SECTION I

INTRODUCTION

Electric vehicles offer what may be ultimate versatility for using alternate fuels. They can be operated with petroleum, natural gas, coal, hydro-power, nuclear reactors, geothermal steam, or any other source of energy that can be used by electric utilities. Other potential advantages of electric vehicles are large reductions in air pollutants, low noise, long life, and reliability. These advantages, as well as potential independence from petroleum fuels, have prompted both government and industry to undertake electric vehicle development.

This report documents the results of work completed in 1980. Until that time various design configurations of electric vehicles were being considered by industry, and numerous computer programs had been developed for predicting their performance. However, these programs were extensively detailed, expensive to run, based on different sets of assumptions and analytical approaches, and limited to specific systems. This made it very difficult to compare the performance capabilities and benefits of one design with another or gain insight into complex designs such as the Garrett electromechanically coupled flywheel system. It was also difficult to generate test plans and to formulate optimum strategies for a given set of conditions. The Electric and Hybrid Vehicles Project at the Jet Propulsion Laboratory identified the need for a simple parametric model that would evaluate and compare a number of different power trains on a common basis. The accuracy of this model for a specific system would depend upon the accuracies of individual component efficiencies and energy fractions that need to be obtained for selected driving conditions through tests or detailed models. However, the results predicted by this model would prove useful for system-level evaluation and comparison and for identifying potential advantages and limitations of one system over another.

SECTION II

GENERAL DESCRIPTION OF ELECTRIC VEHICLE POWER TRAINS

The power train designs included in this study are:

(1) Conventional non-load-leveled electric drive system.

(2) Electromechanically coupled flywheel system representative of the Garrett design.

(3) Mechanically coupled flywheel system representative of a continuously variable transmission (CVT) system.

(4) Electrically coupled flywheel system.

The conventional system is simplest. A power train schematic is shown in Figure 2-1. The components include a battery, armature and field choppers, motor, and transmission. The electrical energy at the battery terminals passes through the choppers to the motor where it is converted into mechanical energy that is transferred through a gear train to the rear axle. The function of the choppers is to control the motor speed and torque by regulating the armature and field currents.

Since there are a minimum number of components in the power train, the efficiency of this design is generally high. Unfortunately, high peak-to-average currents that are generally required of the battery adversely affect usable battery energy and vehicle range. If a higher power density battery is used, it is often at further sacrifice of battery capacity and range.

In order to overcome these drawbacks, flywheel systems have been considered. The flywheel stores excess energy available during off-peak periods and supplements the battery during peak periods. This load leveling will increase the amount of energy that can be obtained from any given battery and will allow selection of batteries with reduced plate area, fewer plates, less inert support structure, increased plate thickness, and increased energy density. If properly designed, the flywheel can also increase the vehicle's acceleration capability. On the other hand, flywheels generally reduce the power train efficiency because of the larger number of components and parasitic losses. They are also characterized by higher weight and initial cost and represent increased complexity. Overall performance depends upon the manner in which the flywheel is incorporated into the system and on the component efficiencies.

Figure 2-2 is a schematic block diagram of the electromechanically coupled flyweel system. The electrical energy at the battery terminals splits into two paths at Point A in the figure. A fraction (x) of this energy passes through the motor and transmission to the rear axle as in a conventional electric drive system. The remaining energy fraction (1-x) passes to the flywheel through the generator and transmission. It is referred to as <u>the</u>

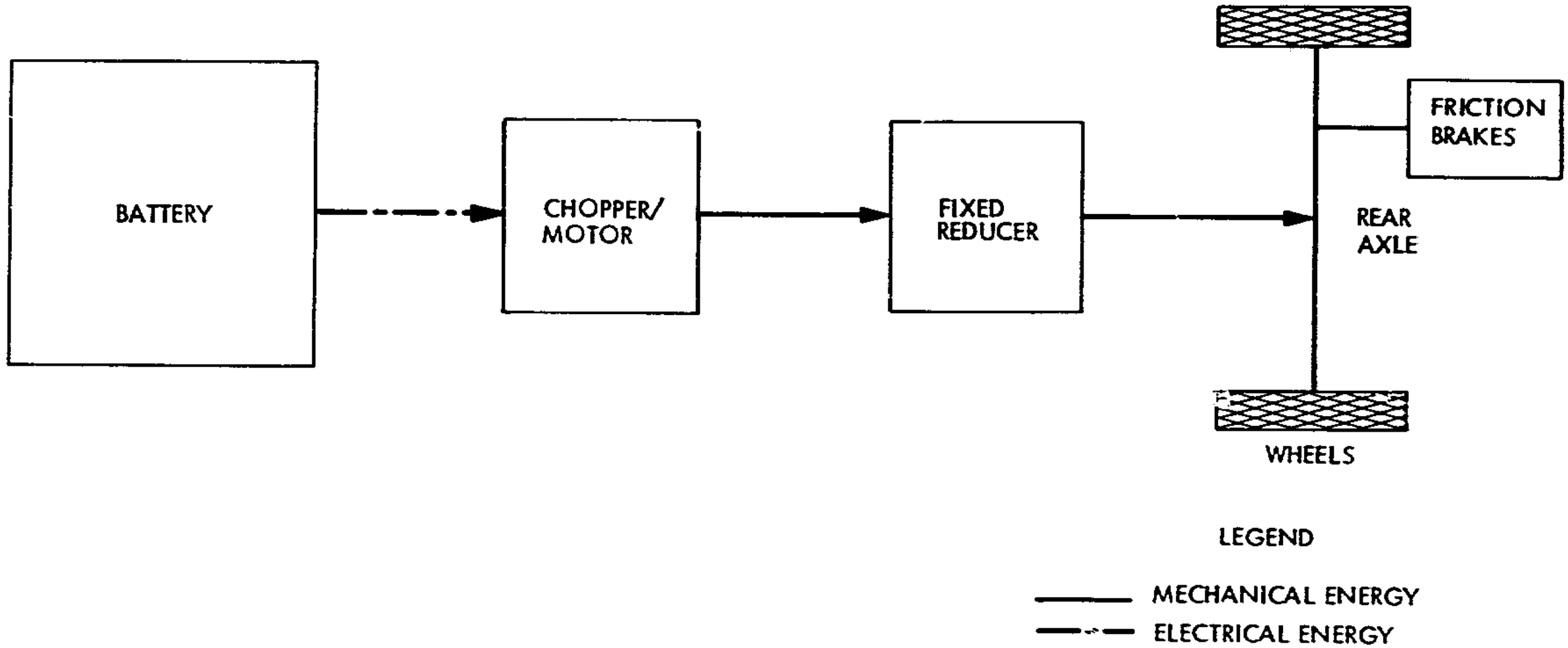

Figure 2-1. Simplified Block Diagram of a Conventional Electric Drive System

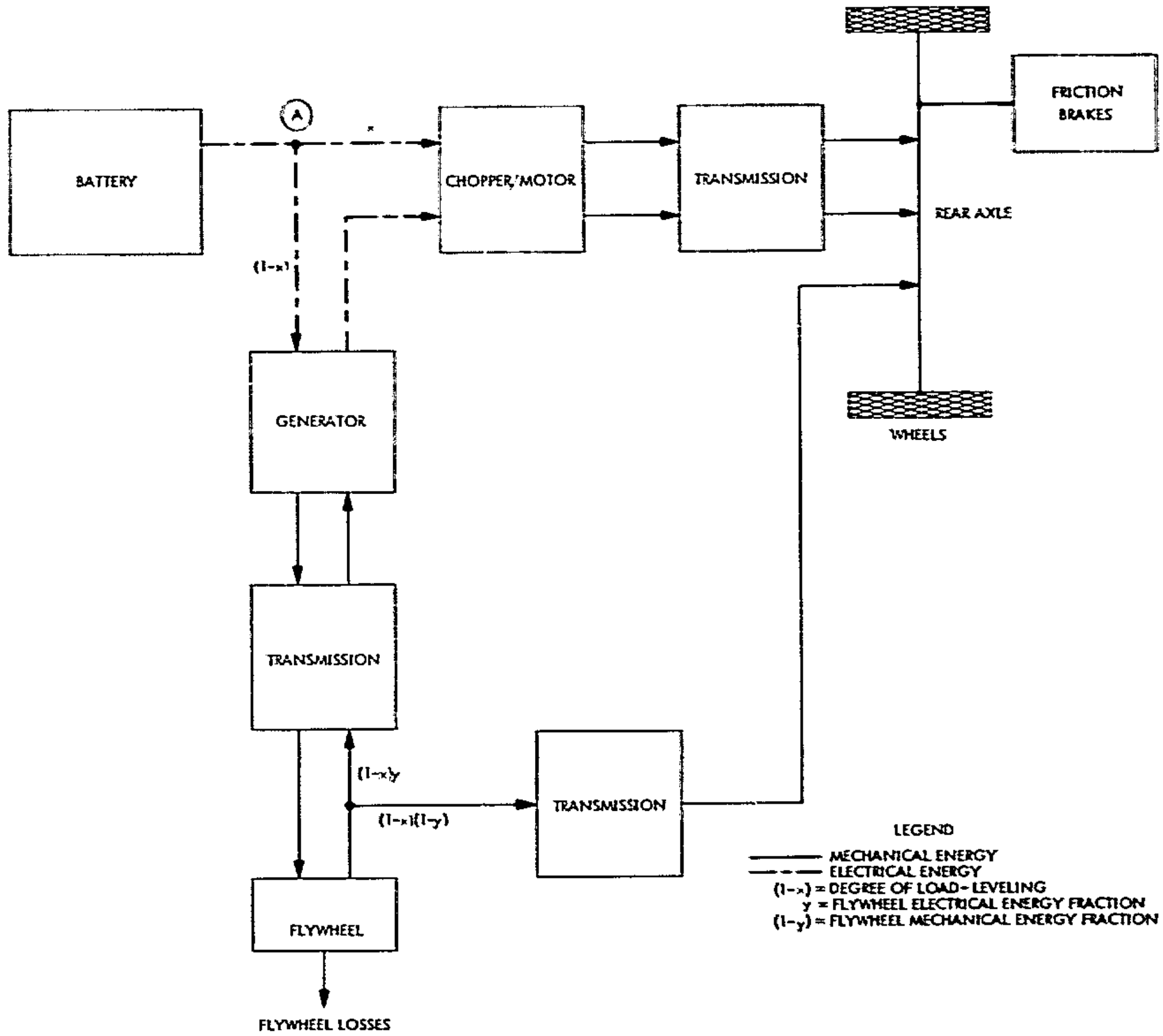

Figure 2-2. Simplified Block Diagram of Electromechanically Coupled Flywheel System

degree of load leveling. The generator converts electrical energy into mechanical energy prior to transmitting it to the flywheel and vice versa when transmitting energy from the flywheel. The flywheel has to be kept running whenever the vehicle is operating, and energy is consumed in merely overcoming speed and bearing losses, as shown in the figure. The net energy stored in the flywheel can be transmitted to the rear axle via two different paths, the electrical path and the mechanical path. As can be seen from the figure, fraction y of the flywheel energy passes through the transmission, generator, and motor to the rear axle. This path is arbitrarily referred to as the electrical path. In the electrical path the generator converts the mechanical energy of the flywheel into electrical energy and the motor reconverts electrical energy into mechanical energy. The remaining flywheel energy, designated as fraction (1-y), is transferred directly to the rear axle through a transmission. This is designated as the mechanical path since the flywheel mechanical energy is directly transferred to the rear axle without conversion to electrical energy as in the electrical path. The schematic shows separate transmissions for the electrical and mechanical paths for simplicity of explanation. However, a single transmission can suffice, as in the Garrett system, in which a single planetary transmission combines both mechanical and electrical power path outputs in a single output shaft.

In a mechanically coupled system, which requires a CVT, the electrical path does not exist. All the flywheel energy is transferred through the mechanical path. In an electrically coupled system, the mechanical path does not exist and all the flywheel energy is routed through the electrical path. Possible design configurations for mechanically and electrically coupled systems are shown in Figures 2-3 and 2-4, respectively.

In electrically and electromechanically coupled systems, the generator acts as a buffer between the road and the flywheel. This enables a wide variation of road speeds at a relatively constant flywheel speed. In a mechanically coupled system, this function is carried out by the CVT.

All of the systems described can recover some energy normally dissipated as heat in the brakes by employing regenerative braking. This will improve vehicle efficiency and range. The energy recovered at the brakes is routed backward through the power train and is stored in the battery in conventional systems and usually in the flywheel in flywheel systems.

In regenerative flywheel systems, the regenerative energy would be routed to and from the flywheel and rear axle via the electrical path in an electrically coupled system, via the mechanical path in the CVT system, and through both paths in an electromechanically coupled system.

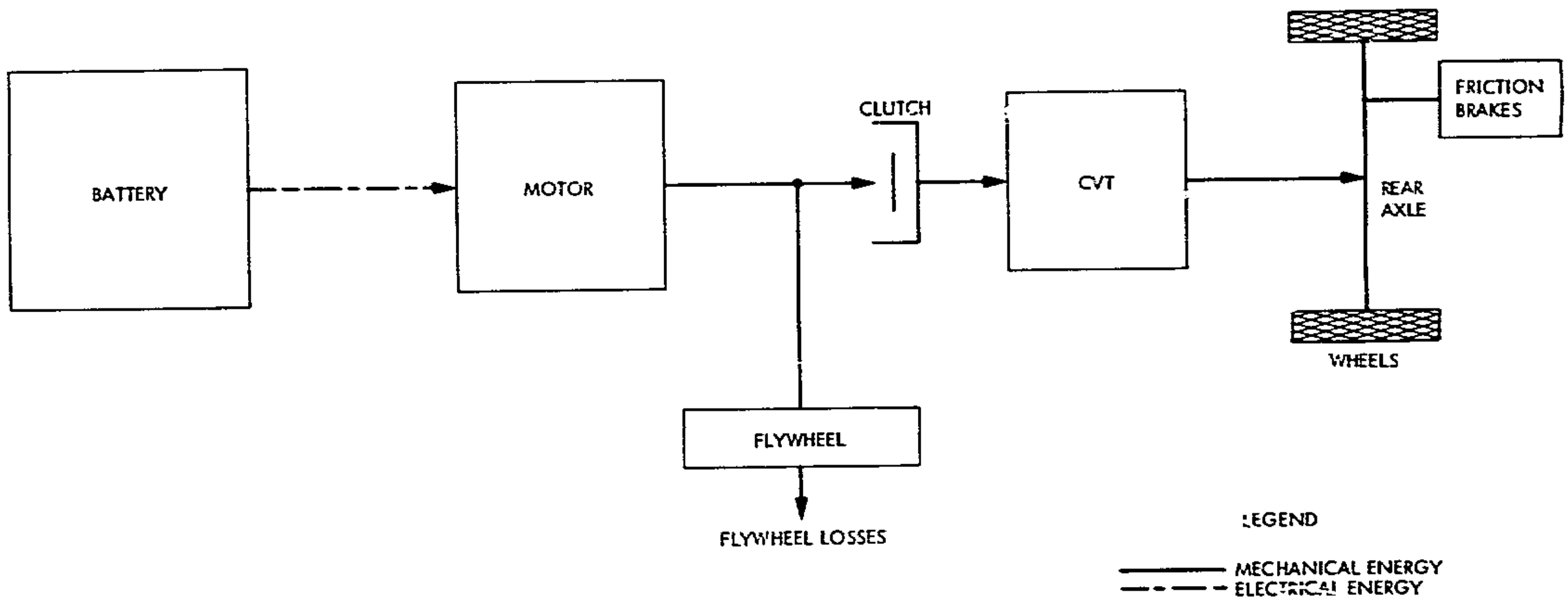

Figure 2-3. Simplified Block Diagram of Mechanically Coupled Flywheel System (CVT)

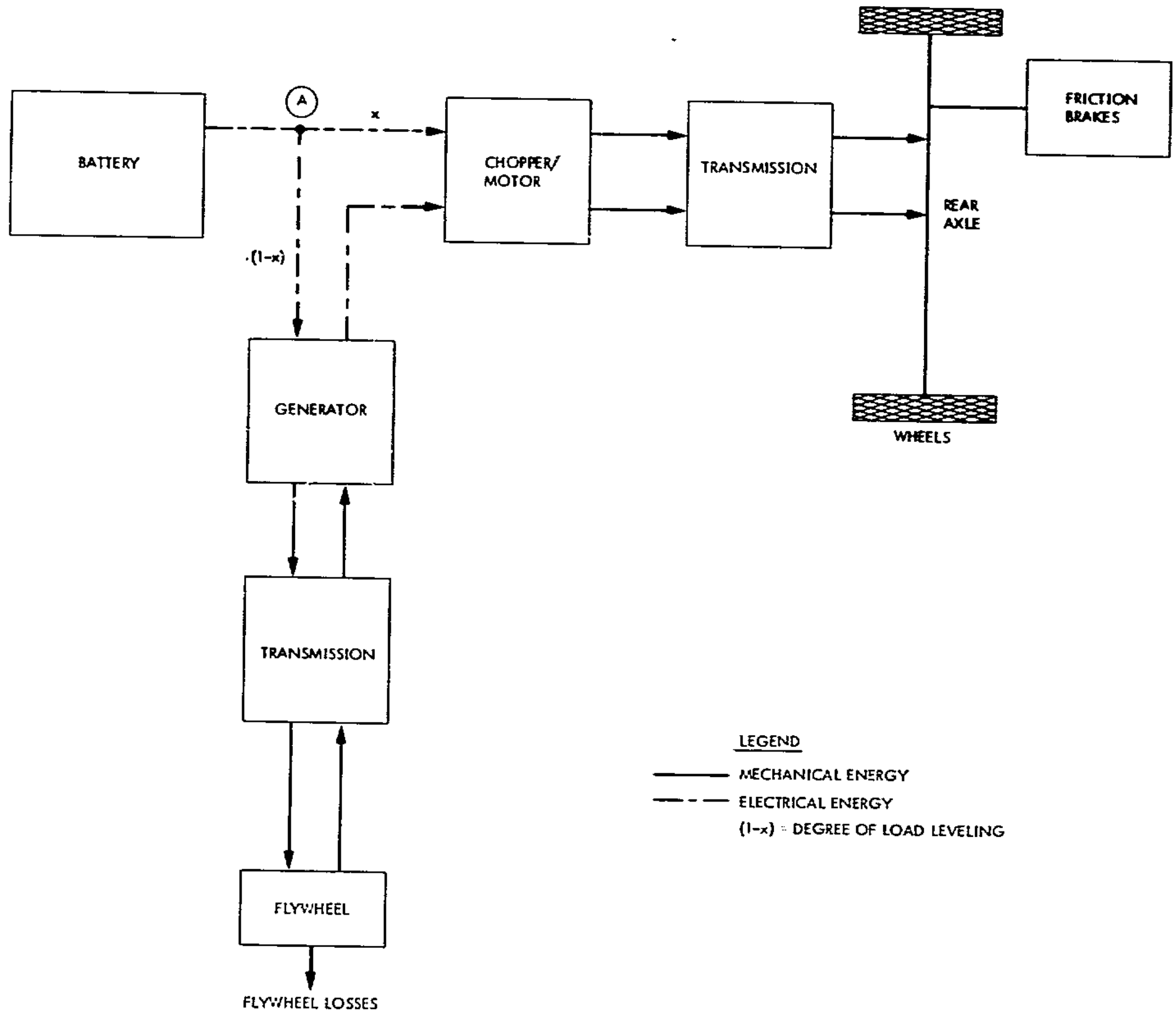

Figure 2-4. Simplified Block Diagram of Electrically Coupled Flywheel System

SECTION III

DESCRIPTION OF MATHEMATICAL MODEL

As a first step in developing the mathematical model, power train efficiency, propulsion system efficiency, and regeneration efficiency were defined.

Power train efficiency (η_{PT}) characterizes the flow of power from the battery terminals to the rear axle. For the purposes of this definition, the battery is not included as part of the power train. For the conventional electric power train, η_{PT} equals the product of the chopper/motor efficiency times the transmission efficiency. No regenerative energy is considered. Average power train efficiency for any configuration is equal to the amount of energy consumed in overcoming rolling resistance and aerodynamic drag, plus that required for braking divided by the amount supplied by the battery. It can be expressed as

$$\eta_{PT} = \frac{E_{RR} + E_{AERO} + E_{BR}}{E_{BAT}} \qquad (1)$$

Note that the energy required for braking is the same as the energy required to accelerate the vehicle.

Propulsion system efficiency (η_{SYS}) was first defined by Garrett AiResearch. It characterizes the flow of power from the battery terminals all the way to the wheel-road interface. Basically, the above-defined Equation (1) system has been expanded to include the brakes. This is convenient when comparing regenerative systems. It combines power train efficiency and regeneration efficiency to directly correlate with range. η_{SYS} can be expressed as

$$\eta_{SYS} = \frac{E_{RR} + E_{AERO}}{E_{BAT}} \qquad (2)$$

For non-regenerative system Equations (1) and (2) can be combined to yield

$$\eta_{SYS} = \eta_{PT} - \frac{E_{BR}}{E_{BAT}} \qquad (3)$$

Further, defining e as energy consumed or delivered per unit distance traveled, Equation (2) for a non-regenerative system as can be rewritten

$$\eta_{SYS} = \frac{e_{RR} + e_{AERO}}{e_{BAT}} \qquad (4)$$

Knowing that $E = eR$, Equation (2) can also be written as:

$$\eta_{SYS} = \frac{e_{RR} + e_{AERO}}{E_{BAT}} \times R \quad (5)$$

where R is the vehicle range.

It can also be seen from Equation (3) that for a non-regenerative system η_{SYS} is less than η_{PT} because of the energy wasted in the brakes. For regenerative systems, the amount wasted as heat depends on the amount available for regeneration and on the regeneration efficiency (η_{REG}). The former is determined by such design considerations as whether or not regenerative braking is employed on all four wheels and whether a boost regulator is used to maintain voltage at minimum charging levels. For convenience, a factor f is defined where f is the amount of energy available for regeneration divided by the total amount required for braking, E_{BR}. Regeneration efficiency is defined as the amount of energy passing from the brakes through the power train into and out of the storage device and back through the power train to the rear axle, divided by the amount of energy regenerated at the rear axle.

For a conventional system, the regeneration efficiency would equal the battery charge-discharge efficiency, multiplied by the square of the power train efficiency:

$$\eta_{REG} = \eta_m^2 \, \eta_{mt}^2 \, \eta_{bcd} = \eta_{PT}^2 \, \eta_{bcd} \quad (6)$$

where η_{pt}^2 represents the power train losses for flow of regeneration energy from the rear axle to the battery and back to the rear axle in round trip, and η_{bcd} represents the battery charge-discharge efficiency.

Thus, for a regenerative conventional electric drive system, the battery energy can be reduced by an amount equal to $e_{BR} f \, \eta_{bcd} \, \eta_{PT}$ where $e_{BR} f \, \eta_{bcd} \, \eta_{PT}$ represents the regeneration energy recovered from the brakes and stored into the battery. The battery energy required is thus $e_{BAT} - e_{BR} f \, \eta_{bcd} \, \eta_{PT}$ and the system efficiency is written as:

$$\eta_{SYS-REG} = \frac{e_{RR} + e_{AERO}}{e_{BAT} - e_{BR} f \, \eta_{bcd} \, \eta_{PT}} \quad (7)$$

Recalling that $E = eR$, Equation (7) can also be written as:

$$\eta_{SYS-REG} = \frac{e_{RR} + e_{AERO}}{E_{BAT}} \times R_{REG} \quad (8)$$

Where R_{REG} is the vehicle range of regenerated system. Note that equation (8) is similar to Equation (5) for the non-regenerated system.

Because gross battery energy increases if regenerated energy is passed back to the battery, a better basis for comparison is original battery energy. This is the energy supplied by the terminals which is originally stored in the battery. It equals gross energy out of the battery minus the product of regenerative energy into the battery multiplied by battery charge-discharge efficiency.

Using this basis for comparison tends to ignore a slight advantage in range for the conventional system because of depolarization effects during regenerative charging, but this effect is believed to be less than 5%.

Setting Equation (7) equal to Equation (8), solving for R_{REG}, and multiplying both the numerator and denominator by η_{PT} gives

$$R_{REG} = \frac{E_{BAT}\ \eta_{PT}}{e_{BAT}\ \eta_{PT} - e_{BR}\ f\ \eta_{PT}^2\ \eta_{bcd}} \tag{9}$$

Substituting $e_{RR} + e_{AERO} + e_{BR}$ for $e_{BAT}\ \eta_{PT}$ provides

$$R_{REG} = \frac{E_{BAT}\ \eta_{PT}}{e_{RR} + e_{AERO} + e_{BR}\ (1 - f\ \eta_{PT}^2 \eta_{bcd})} \tag{10}$$

Because this calculation was based on a conventional electric system, $\eta_{PT}{}^2\eta_{bcd}$ can be replaced by η_{REG}, according to Equation (6)

$$R_{REG} = \frac{E_{BAT}\ \eta_{PT}}{e_{RR} + e_{AERO} + e_{BR}\ (1 - f\ \eta_{REG})} \tag{11}$$

For electromechanical, electrical, and CVT systems, Equations (6), (7), (9), and (10) would have to be modified. However, through the use of series expansions, it has been confirmed that the form of Equation (11) remains unchanged. Equation (11) is applicable to all the configurations discussed. For non-regenerative systems, $f = 0$ and Equation (11) becomes

$$R = \frac{E_{BAT}\ \eta_{PT}}{e_{RR} + e_{AERO} + e_{BR}} \tag{12}$$

After deriving the above equations, flow charts were developed to simulate energy flow and losses through the motor, generator, transmissions, and flywheel (Figures 3-1 and 3-2).

Algebraic expressions were then developed for the basic efficiency terms. The model is general enough to allow simulation of a variety of systems, including conventional non-load-leveled systems, electromechanically coupled systems, CVT systems, and electrically coupled systems. An obvious assumption is that reasonably accurate information on component efficiencies and various energy fractions are available, either from actual test data or from detailed analytical predictions.

As the energy flows through each component, it is multiplied by a corresponding efficiency to account for losses. For example, in Figure 3-1, as the battery energy fraction x passes through the chopper/motor, it is multiplied by motor efficiency η_m, and then by η_{mt} as it passes through the transmission. Thus, the net energy available at the rear axle through the motor path equals

$$x \, \eta_m \, \eta_{mt}$$

Similarly, as the remaining battery energy fraction 1-x passes through the generator and transmission to the flywheel, it is multiplied by corresponding efficiencies. The energy going into the flywheel thus equals $(1-x)\,\eta_g\,\eta_{gt}$. There are load and speed-related losses associated with the use of the flywheel. The load-related losses, as opposed to the speed-related parasitic losses, are lumped into generator-transmission efficiency. The speed-related losses are subtracted from the flywheel energy. The net energy received by the flywheel thus equals $(1-x)\eta_g\eta_{gt}-F_\ell$, where F_ℓ represents the fraction of gross battery energy lost because of speed-related losses in the flywheel. The fraction y of the outgoing flywheel energy goes to the rear axle via the motor-generator set and related transmissions. The net energy available at the rear axle through this path thus equals

$$\left[(1-x)\,\eta_g\,\eta_{gt} - F_\ell\right]\, y\, \eta_{gt}\,\eta_g\,\eta_m\,\eta_{mt}$$

The remaining fraction of outgoing flywheel energy (1-y) passes to the rear axle through the mechanical path. The net energy available at the rear axle through the mechanical path thus equals

$$\left[(1-x)\,\eta_g\,\eta_{gt} - F_\ell\right]\,(1-y)\,\eta_{ft}$$

The total energy available at the rear axle is the sum of energy available through all the three paths and takes into account all the power train losses. The algebraic equation for the power train efficiency of an electromechanically coupled system is the sum of the energy fractions from these three paths given as

$$\eta_{PT} = x\eta_m\eta_{mt} + \left[(1-x)\,\eta_g\eta_{gt} - F_\ell\right]\, y\eta_{gt}\eta_g\eta_m\eta_{mt} + \left[(1-x)\,\eta_g\eta_{gt} - F_\ell\right]\,(1-y)\,\eta_{ft} \tag{13}$$

In the above equation, F_ℓ represents gross speed-related losses that the battery must supply to the flywheel. The gross losses equal net losses dissipated in the flywheel, divided by the generator and transmission efficiencies. In recent tests of the Garrett system with a 7-kWh battery, the

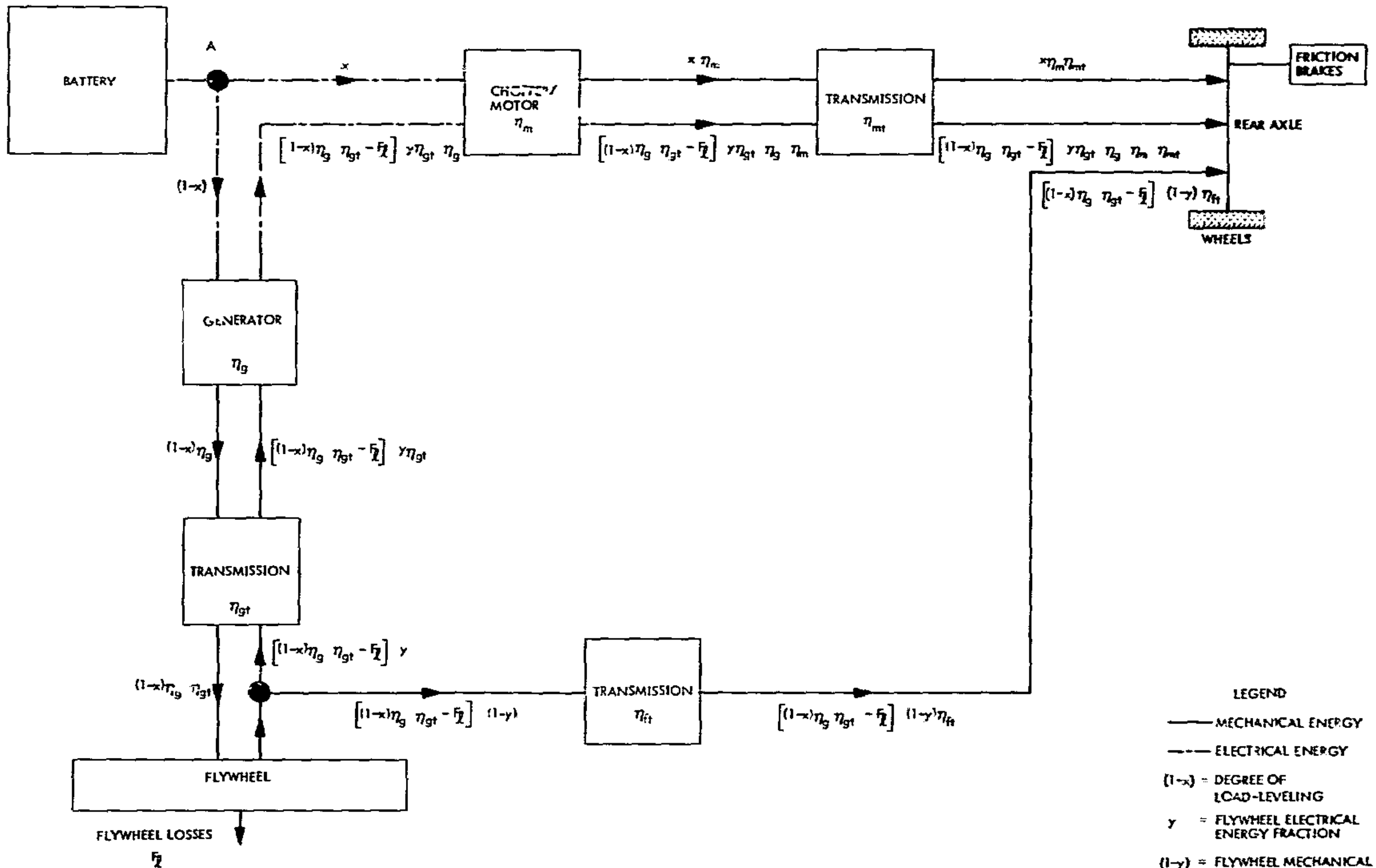

Figure 3-1. Energy Flow in the Power Train of Electromechanically Coupled Flywheel System

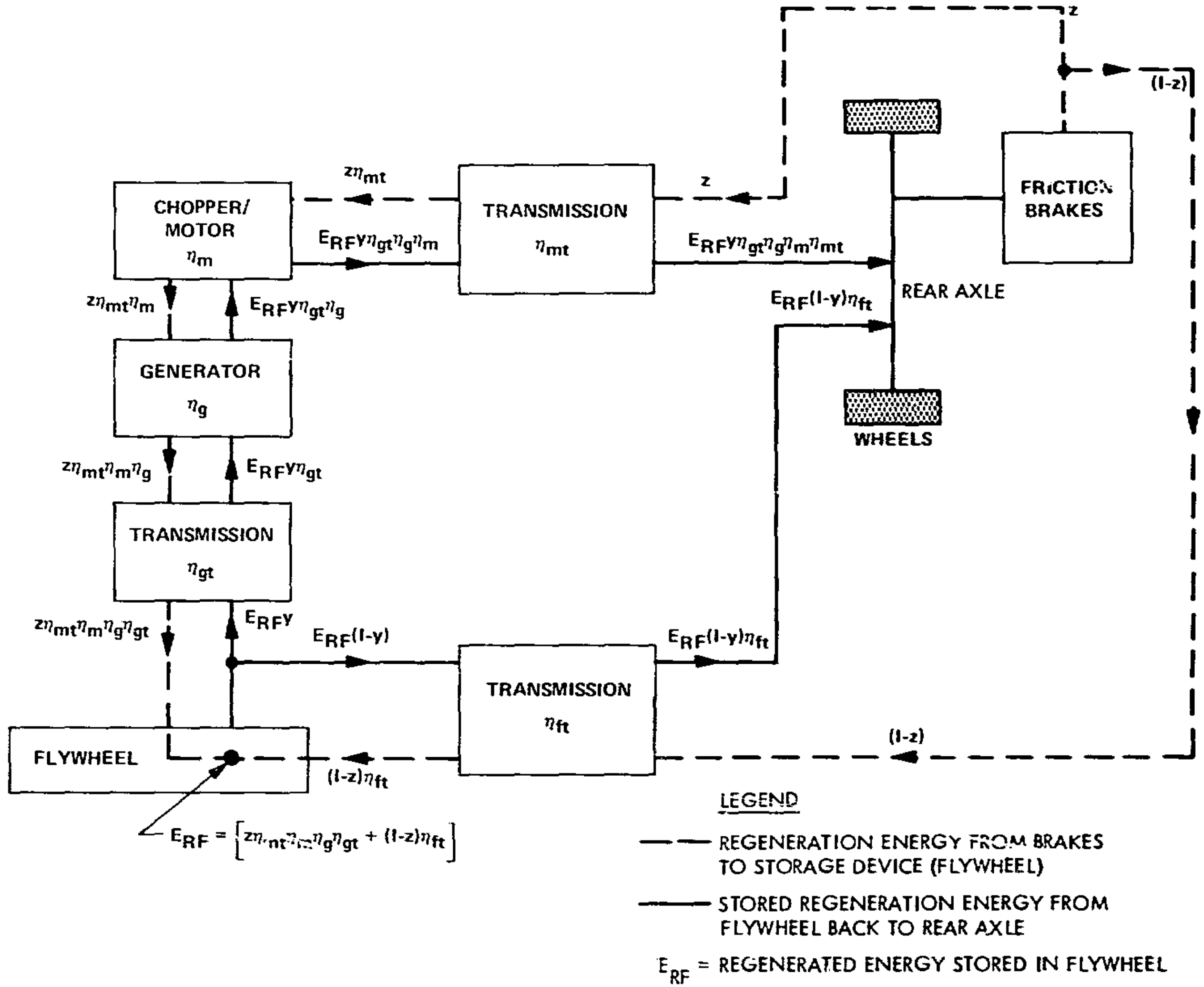

Figure 3-2. Regeneration Energy Loop in Electromethanically Coupled Flywheel System

net flywheel speed-related losses were found to be about 420 Wh or 6% of the battery energy. In order to meet this demand at the flywheel, the battery will have to supply $6\%/\eta_g \eta_{gt}$ or 7.7% of the energy, assuming $\eta_g = 0.85$ and $\eta_{gt} = 0.92$. The gross flywheel losses thus equal 7.7% of the battery energy.

In the present model, the chopper losses are included as a part of motor efficiency. This is a reasonable assumption because these losses are negligible except for very low motor speeds.

Equation (13) is for the power train efficiency of an electromechanically coupled system, representative of the Garrett design.

Note that if x is equal to 1.0 and y and F_ℓ are set equal to 0.0, Equation (13) reduces down to $\eta_{PT} = \eta_m \eta_{mt}$ which is the expression for power train efficiency for a conventional electric system.

Further if y is set equal to 0.0 Equation (13) reduces to the power train efficiency of CVT system and if y is set equal to 1.0, Equation (13) reduces to the power train efficiency of an electrically coupled system.

To account for regeneration, a similar procedure was followed for the regenerative loop. Figure 3-2 represents this loop in an electromechanically coupled system. The energy recovered at the brake flows bi-directionally within the system. The Fraction z of the usable braking energy is regenerated through the electrical loop (through the motor-generator set), while the remaining energy fraction (1-z) is regenerated through the mechanical loop. During regeneration the motor also acts as a generator, i.e., converts mechanical energy into electrical energy during flow of energy from the brakes to the system.

The equation for regeneration efficiency is derived as

$$\eta_{REG} = E_{RF} \left[y \eta_{gt} \eta_g \eta_m \eta_{mt} + (1-y)\ \eta_{ft} \right] \tag{14}$$

where E_{RF} is the regenerated energy stored in the flywheel given as

$$E_{RF} = z \eta_{mt} \eta_m \eta_g \eta_{gt} + (1-z)\ \eta_{ft} \tag{15}$$

In Equations (14) and (15) if y and z are set equal to 0.0, they represent regeneration efficiency of the CVT system. On the other hand, setting y and z equal to 1.0, yields the regeneration efficiency of the electrically coupled system.

As opposed to flywheel systems, regeneration in conventional systems takes place through the battery and associated battery charge-discharge losses have to be included. For such a system, therefore, the equation for regeneration efficiency is as given earlier by Equation (6).

Results presented in the following section were obtained using efficiencies and energy fractions representative of today's state of the art

Table 3-1. Power Train Trade-off Matrix

Parameter	. generated Conventional Non-load-leveled Electric Drive System	Regenerated Electro-mechanically Coupled Flywheel System (Garrett-Type)	Regenerated Electro-mechanically Coupled System, (Future Garrett-Type)	Regenerated Mechanically Coupled Flywheel System (CVT)	Regenerated Electrically Coupled Flywheel System
Nominal	X	X	X	X	X
Increased battery charge-discharge efficiency	X	N/A	N/A	N/A	N/A
Increased transmission efficiencies	X	X	X	X	X
Increased motor-generator efficiencies	X	X	X	X	X
Increased degree of load leveling	N/A	X	X	X	X
Increased degree of regeneration	X	X	X	X	X
Varying flywheel mechanical and electrical energy fractions	N/A	X	X	N/A	N/A
Reducing flywheel losses	N/A	X	X	X	X

and are based on an SAE J227-D driving cycle. The cases examined are listed in Table 3-1 and the values assumed are summarized in Table 3-2.

In general, η_{PT} was calculated using Equation (13), and η_{REG} was calculated using Equations (6), (14), and (15). These were then substituted in Equation (11) to calculate range. Range was then substituted into Equation (8) to provide propulsion system efficiency.

Table 3-2. Nominal Component Efficiencies and Energy Fractions Representative of the SAE J227 a-D Driving Cycle

Original battery energy, E_{BAT}	14 kWh
Gross speed-related flywheel parasitic losses, F_ℓ as a fraction of original battery energy	$\frac{0.06}{\eta_g \eta_{gt}}$
Degree of regeneration, f	0.75
Battery charge-discharge efficiency, η_{bcd}	0.8
Generator efficiency, η_g	0.85
Motor efficiency, η_m	0.85
Transmission efficiencies, $\eta_{ft} = \eta_{gt} = \eta_{mt}$	0.92
Specific energy going into rolling resistance, e_{RR}	0.059 kWh/km (0.099 kWh/mi)
Specific energy going into aerodynamic drag, e_{AERO}	0.041 kWh/km (0.066 kWh/mi)
Specific energy going into brakes, e_{BR}	0.0487 kWh/km (0.0784 kWh/mi)

SECTION IV

RESULTS

Power train efficiency varies to the first order with motor, generator, and transmission efficiencies, flywheel losses, degree of load leveling, and the flywheel mechanical electrical energy fraction. Results are plotted in Figure 4-1 and tabulated in Table 4-1. The power train efficiency of conventional electric drive system is predicted to be 78.2%. This compares with a spectrum of power train efficiencies for flywheel systems varying from a maximum of 72.5% with zero load leveling to a minimum of 43% with 100% load leveling in an electrically coupled system (at 0% flywheel mechanical energy fraction). It can also be seen from Figure 4-1 that at zero load leveling, the power train efficiencies of all the flywheel systems converge to a single point. Further, at zero load leveling the only difference in the power train efficiency of a conventional electric drive system and the flywheel systems is due to the flywheel losses in the latter. Realistic cases are indicated within the dashed box in the figure. Detailed predictions and variations around the nominal case resulting from minor perturbations in transmission efficiencies, motor-generator efficiencies, and flywheel losses are summarized in Table 4-1. The only difference between the future Garrett system and the present Garrett system is the increased flywheel mechanical energy fraction. As can be seen from Table 4-1, at 50% load leveling, an increase in the mechanical fraction from 0.25 for the present Garrett system to 0.75 for the future Garrett system would increase power train efficiency from 60.7% to 65.6%, an increase of 8%.

Range and propulsion system efficiencies corresponding to the above cases are plotted in Figure 4-2 and tabulated in Table 4-2 for non-regenerative systems. The propulsion system efficiency of a conventional electric drive system is predicted to be 52.6% and compares with a spectrum of propulsion system efficiencies of flywheel systems varying from a maximum of 48.5% at zero load leveling to a minimum of 29% at 100% load leveling in an electrically coupled system (at 0% flywheel mechanical energy fraction). Vehicle range is calculated, assuming typical rolling resistance, drag, and braking energy requirements specified in Table 3-2. It can be seen from Figures 4-1 and 4-2 that the trends between power train efficiencies and propulsion system efficiencies of non-regenerative systems are exactly similar.

Regeneration efficiency is plotted as a function of battery charge-discharge efficiency and component efficiencies for conventional electric drive system in Figure 4-3, and as a function of flywheel mechanical energy fraction and component efficiencies for flywheel systems in Figure 4-4. Further detail is provided in Table 4-3. As can be noted, there is a similarity between the trends in regeneration efficiency and power train efficiency. The nominal regeneration efficiency of a CVT system of 84.6% is significantly higher than the 48.9% predicted for a conventional electric drive system and the 37.4% predicted for an electrically coupled system.

Predicted propulsion system efficiency and vehicle range for systems incorporating regeneration are plotted in Figure 4-5 and tabulated in Table 4-4. Predicted lines do not converge at zero load leveling as in Figures 4-1 and 4-2 because of the effect of the different implementations on regeneration efficiency.

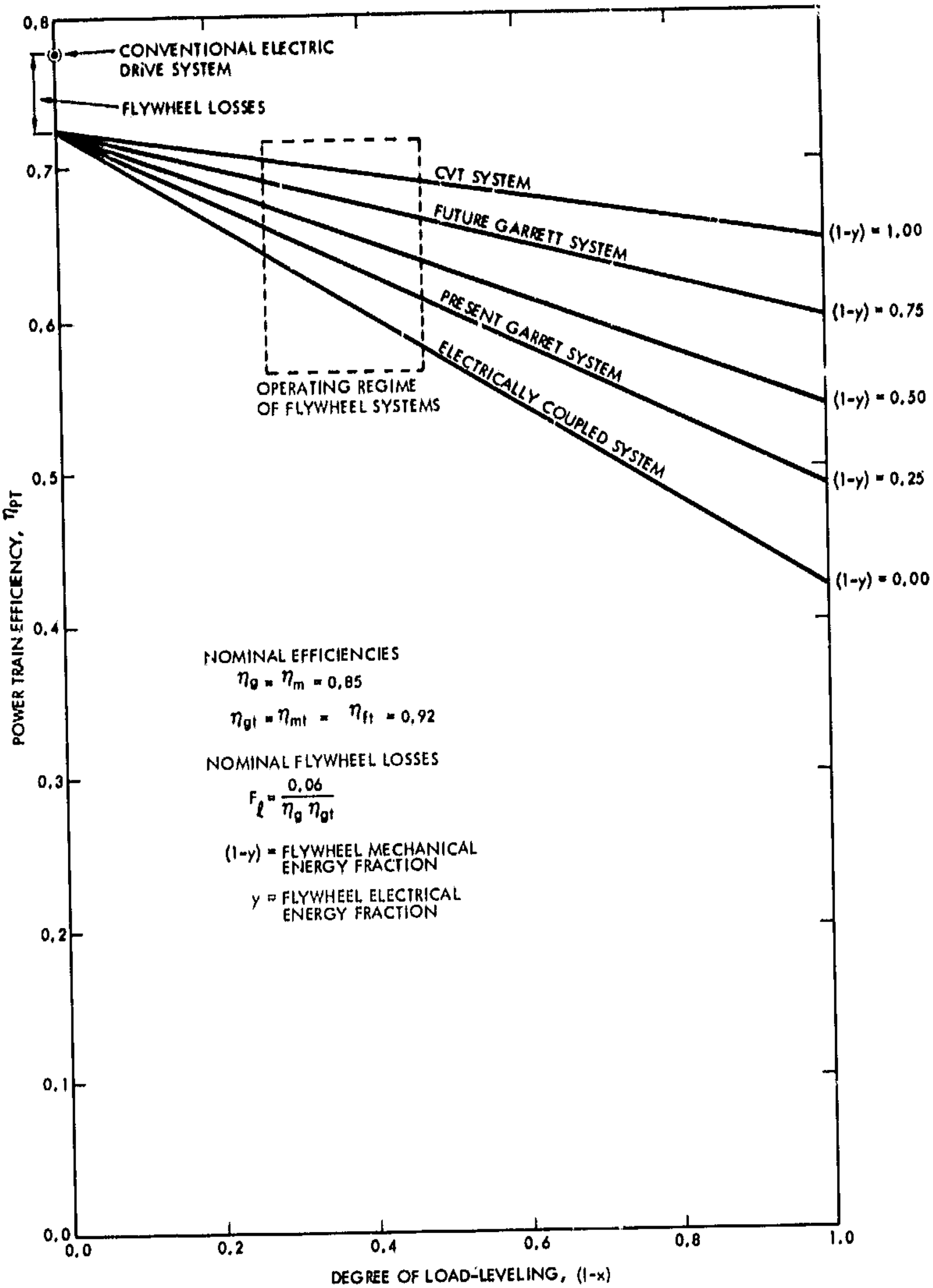

Figure 4-1. Power Train Efficiencies of Various Systems

Table 4-1. Power Train Efficiencies of Various Systems

	Vehicle Type				
	Conventional Electric Drive System	Electromechanically Coupled Flywheel System: Present Garrett System	Electromechanically Coupled Flywheel System: Future Garrett System	Mechanically Coupled Flywheel System (CVT)	Electrically Coupled Flywheel System
Nominal	0.782	0.607	0.656	0.680	0.583
5-percentage-point increase in transmission efficiencies	0.824	0.667	0.716	0.741	0.643
5-percentage-point increase in motor-generator efficiencies	0.828	0.668	0.710	0.728	0.648
5-percentage-point increase in transmission plus motor-generator efficiencies	0.873	0.735	0.773	0.792	0.716
50-percent reduction in flywheel losses	N/A	0.634	0.688	0.715	0.606
5-percentage-point increase in transmission and motor-generator efficiencies plus 50-percent reduction in flywheel losses	N/A	0.764	0.806	0.826	0.743

Note: Flywheel systems are evaluated at degree of load leveling, (1-x)=0.5.

A bar chart summarizing all the results is presented in Figure 4-6. A comparison is made between each type of system. The figure also shows the improvement in propulsion system efficiency and range that can be achieved by adding and enhancing regeneration, reducing flywheel losses, and improving component efficiencies.

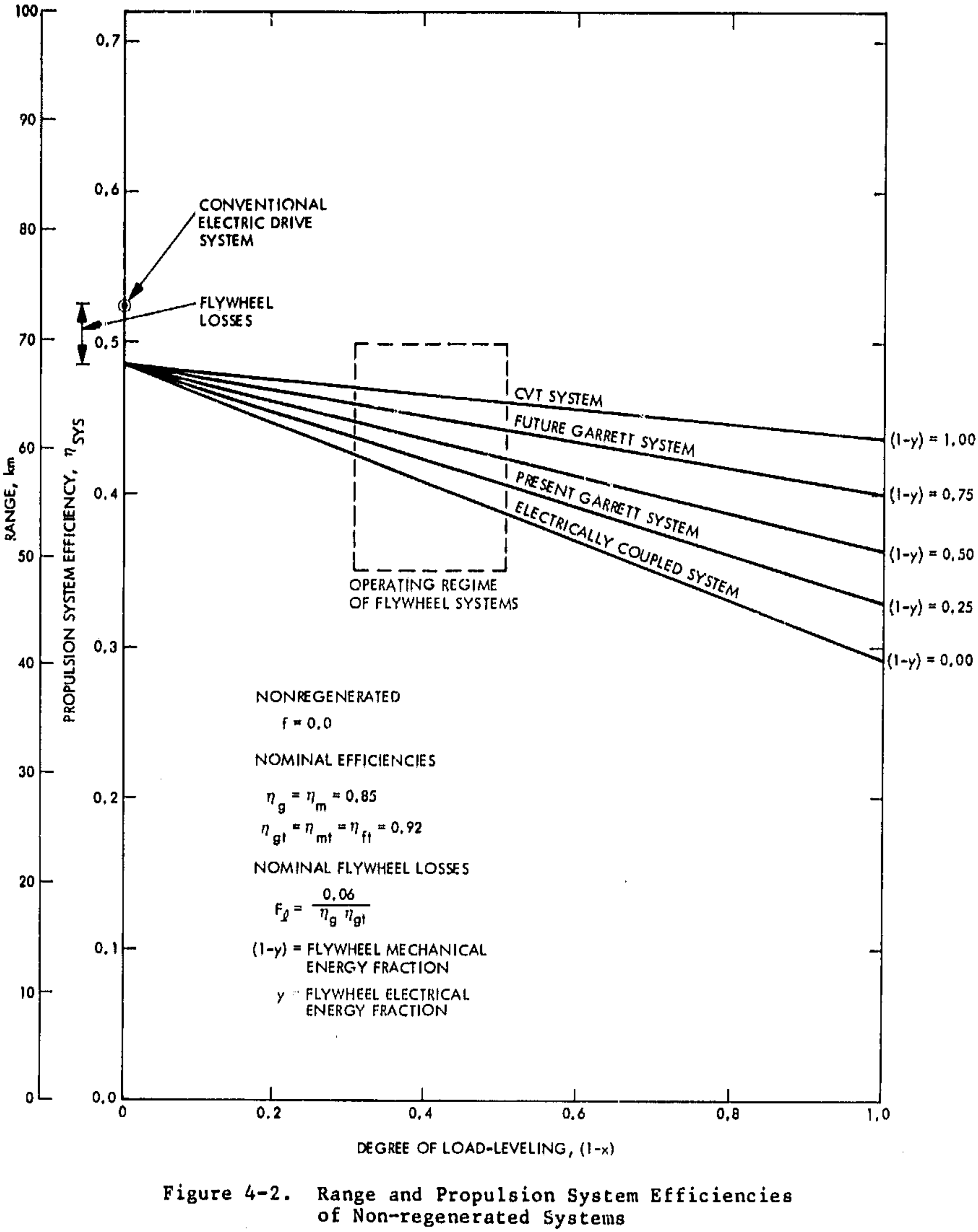

Figure 4-2. Range and Propulsion System Efficiencies of Non-regenerated Systems

Table 4-2. Range and Propulsion System Efficiencies of Non-regenerated Systems

	Vehicle Type									
	Conventional Electric Drive System		Electromechanically Coupled Flywheel System: Present Garrett System		Electromechanically Coupled Flywheel System: Future Garrett System		Mechanically Coupled Flywheel System (CVT)		Electrically Coupled Flywheel System	
	System Effi- ciency, η_{SYS}	Vehicle Range, km	System Effi- ciency, η_{SYS}	Vehicle Range, km	System Effi- ciency, η_{SYS}	Vehicle Range, km	System Effi- ciency, η_{SYS}	Vehicle Range, km	System Effi- ciency, η_{SYS}	Vehicle Range, km
Nominal	0.526	73.6	0.408	57.1	0.441	61.7	0.457	64.0	0.392	54.9
5-percentage-point increase in transmission efficiencies	0.554	77.6	0.448	62.7	0.481	67.3	0.497	69.6	0.432	60.5
5-percentage-point increase in motor-generator efficiencies	0.557	78.0	0.449	62.9	0.477	66.8	0.489	68.5	0.436	61.0
5-percentage-point increase in transmission plus motor-generator efficiencies	0.587	82.2	0.494	69.2	0.512	71.7	0.533	74.6	0.481	67.3
50% reduction in flywheel losses	N/A	N/A	0.426	59.7	0.462	64.7	0.481	67.3	0.407	57.0
5-percentage point increase in transmission plus motor-generator efficiences plus 50% reduction in flywheel losses	N/A	N/A	0.513	71.9	0.541	75.8	0.555	77.7	0.500	69.9

Note: All flywheel systems are evaluated at degree of load leveling, $(1-x) = 0.5$.

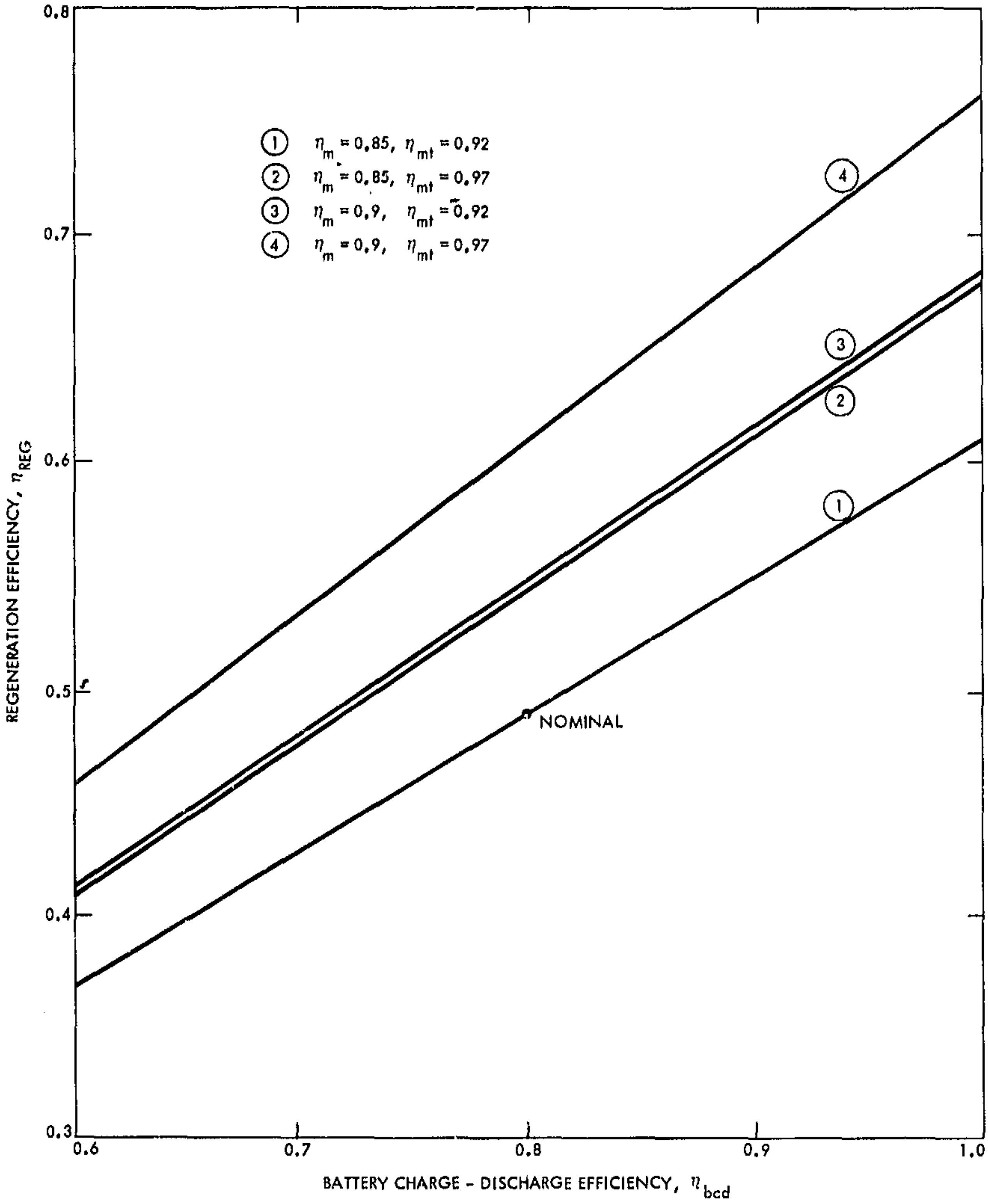

Figure 4-3. Regeneration Efficiencies of Conventional Electric Drive System

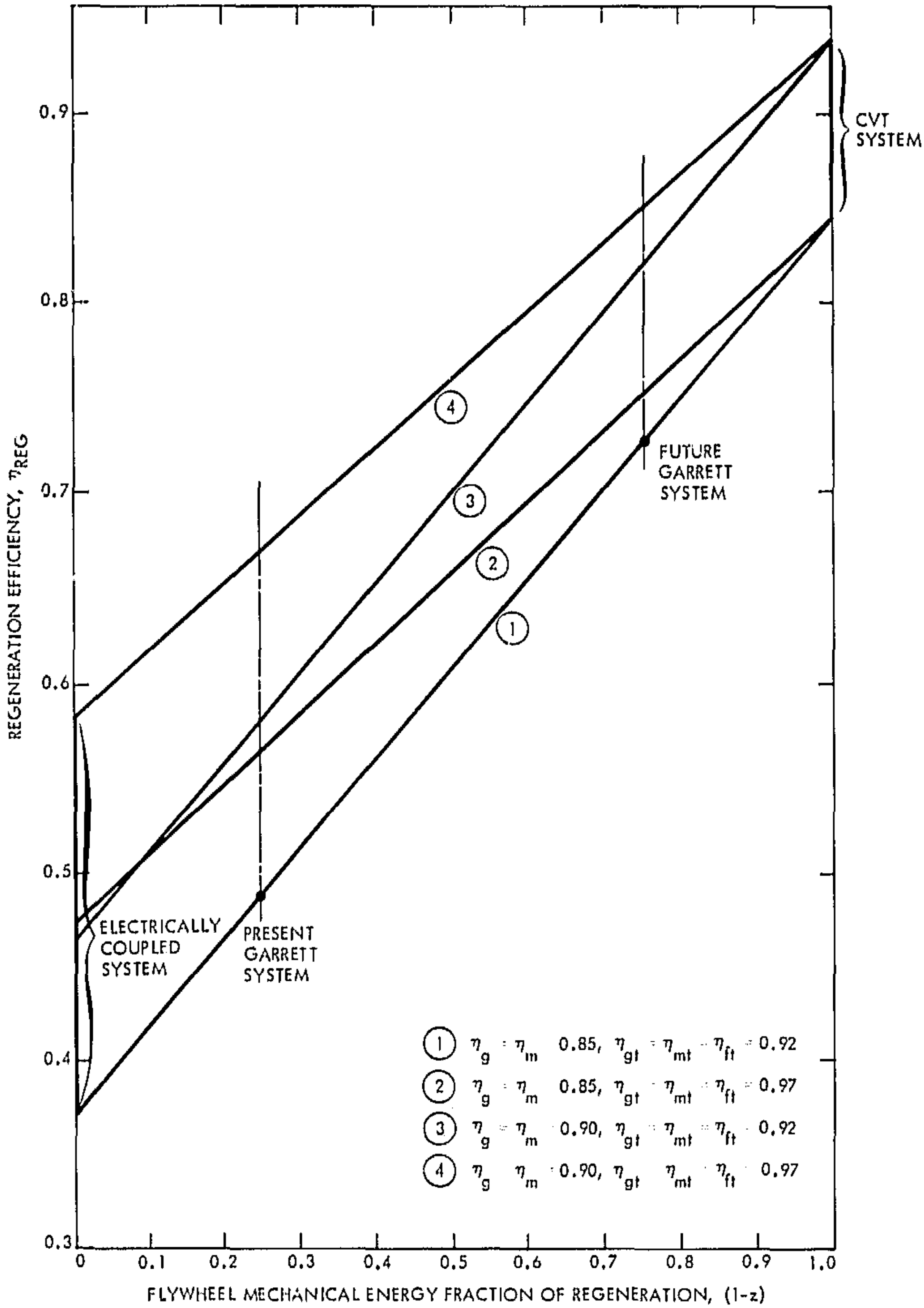

Figure 4-4. Regeneration Efficiencies of Various Flywheel Systems

Table 4-3. Regeneration Efficiencies

	Vehicle Type				
		Electro-mechanically Coupled Flywheel System			
	Conventional Electric Drive System	Present Garrett System	Future Garrett System	Mechanically Coupled Flywheel System (CVT)	Electrically Coupled Flywheel System
Nominal	0.489	0.473	0.710	0.846	0.374
5-percentage-point increase in battery charge-discharge efficiency	0.520	N/A	N/A	N/A	N/A
5-percentage-point increase in transmission efficiencies	0.544	0.566	0.805	0.941	0.462
5-percentage-point increase in motor-generator efficiencies	0.548	0.554	0.742	0.846	0.470
5-percentage-point increase in transmission and motor-generator efficiencies	0.610	0.663	0.842	0.941	0.580

Figures 4-1, 4-2, 4-4, 4-5, and 4-6, and Tables 4-1 through 4-4 all indicate that, for the configurations studied, it is more advantageous to transfer energy into and out of the flywheel mechanically than electrically. There are fewer components and hence higher power train efficiency.

The results also suggest that there is an optimum degree of load leveling which depends on the driving cycle, battery characteristics, the mode of mechanizing the load leveling system, and on the efficiency of the components. Figure 4-5 indicates that for state-of-the-art mechanically coupled (CVT) flywheel systems, load-leveling losses can be held below a reasonable 10% when compared to the conventional electric drive system, but with electrically coupled systems the losses can be up to six times larger. To obtain the optimum design these losses must be traded off against improvements possible from load leveling.

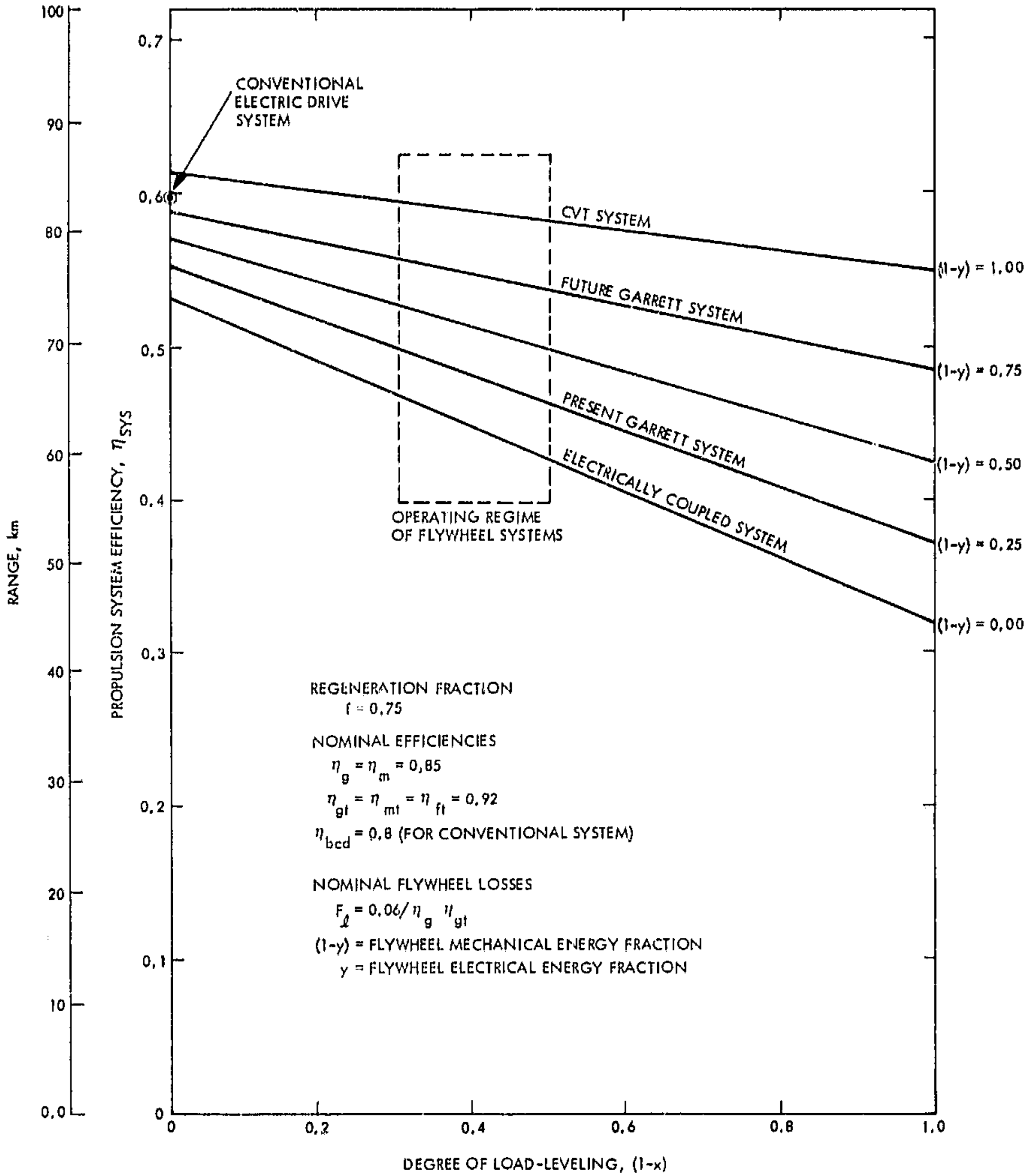

Figure 4-5. Range and Propulsion System Efficiencies of Regenerated Systems

Table 4-4. Range and Propulsion System Efficiencies of Regenerated Systems

	Vehicle Type									
	Conventional Electric Drive System		Electromechanically Coupled Flywheel System: Present Garrett System		Electromechanically Coupled Flywheel System: Future Garrett System		Mechanically Coupled Flywheel System (CVT)		Electrically Coupled Flywheel System	
	System Effi-ciency, η_{SYS}	Vehicle Range, km	System Effi-ciency, η_{SYS}	Vehicle Range, km	System Effi-ciency, η_{SYS}	Vehicle Range, km	System Effi-ciency, η_{SYS}	Vehicle Range, km	System Effi-ciency, η_{SYS}	Vehicle Range, km
Nominal	0.600	83.7	0.462	64.6	0.534	74.7	0.577	80.7	0.432	60.4
5-percentage-point increase in battery charge-discharge efficiency	0.603	84.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5-percentage-point increase in transmission efficiencies	0.640	89.5	0.520	72.7	0.600	83.9	0.648	90.6	0.488	68.2
5-percentage-point increase in motor-generator efficiencies	0.643	89.9	0.520	72.7	0.584	81.7	0.618	86.4	0.493	68.9
5-percentage-point increase in transmission plus motor-generator efficiencies	0.690	96.5	0.590	82.5	0.655	91.6	0.693	96.9	0.560	78.3
25% increase in degree of regeneration	0.626	87.5	0.483	67.5	0.575	80.4	0.632	88.4	0.450	62.9
50% reduction in flywheel losses	N/A	N/A	0.475	66.4	0.560	78.3	0.620	86.7	0.447	62.5
5-percentage point increase in transmission and motor-generator efficiences plus 25% increase in degree of regeneration plus 50% reduction in flywheel losses	0.710	99.3	0.660	92.3	0.750	104.9	0.800	111.9	0.620	86.7

Note: All flywheel systems are evaluated at degree of load leveling, $(1-x) = 0.5$.

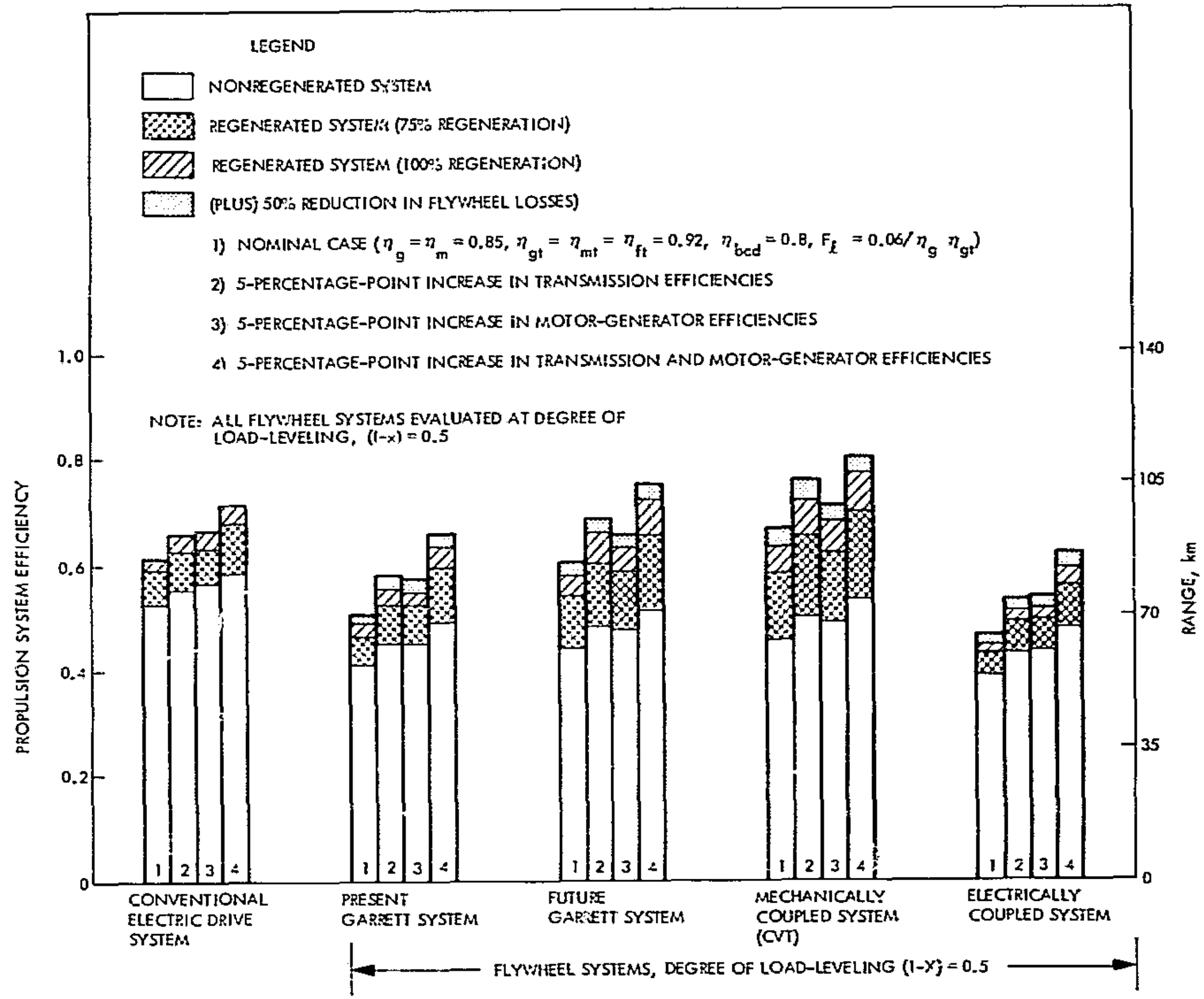

Figure 4-6. Range and Propulsion System Efficiencies of all the Systems Considered in Present Study

Figure 4-5 also indicates that the propulsion system efficiency for state-of-the-art mechanically coupled flywheel systems is about equal to the 60% achieved on conventional non-load-leveled systems. This is approximately 15% more efficient at zero-load-leveling and 90% more efficient at full load-leveling than electrically coupled flywheel systems.

Table 4-4 indicates that increasing the flywheel mechanical-to-electrical energy fraction on Garrett's system from 0.25 to 0.75 would increase propulsion system efficiency from 46.2 to 53.4%, an improvement of 15%. If this fraction were further increased to its maximum of 1.0, (i.e., a CVT system) flywheel parasitic losses reduced 50%, component efficiencies increased 5 percentage-points and the degree of regeneration increased from 75 to 100%, the propulsion system efficiency would be increased to nearly 80%, as shown in Figure 4-6.

SECTION V

CONCLUSIONS

The major conclusions are as follows:

(1) For flywheel systems, it is more advantageous to transfer energy into and out of the flywheel mechanically rather than to do it electrically. Therefore, for electromechanically coupled systems, the mechanical-to-electrical energy fraction should be maximized. If mechanical inplementation could be realized, the potential for CVT sytems looks good.

(2) For flywheel systems there is an optimum degree of load leveling which depends on the driving cycle, battery characteristics, the mode of mechanizing the load leveling system and on the efficiency of components. For state-of-the-art mechanically coupled (CVT) flywheel systems, load leveling losses can be held below a reasonable 10%, but with electrically coupled systems, the losses can be up to six times larger. To obtain the optimum design, these losses must be traded off against improvements in battery performance possible from load leveling.

(3) Propulsion system efficiency for state-of-the-art mechanically coupled systems is about equal to the 60% achieved on conventional non-load-leveled systems. This is approximately 15% more efficient at zero load leveling and 90% more efficient at full load leveling than electrically coupled flywheel systems.

(4) Propulsion system efficiency of about 60% for the state-of-the-art mechanically coupled systems can be increased to as high as 80% by decreasing flywheel parasitic losses to 50%, increasing degree of regeneration to 100% and increasing the component efficiencies by 5 percentage points.

(5) Increasing component efficiencies and/or regeneration fraction is more important for flywheel systems than for conventional systems.

(6) Flywheel losses should be reduced in load-leveled systems.