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HYBRID VEHICLE TECHNOLOGY CONSTRAINTS AND APPLICATION ASSESSMENT STUDY

Volume I: Summary

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Abstract

his four-volume report presents analyses and assessments of both heat engine/attery-and heat engine/flywheel-powered hybrid vehicles to determine if they could ontribute to near-term (1980-1990) reductions in transportation energy consumpion under several sets of operational conditions: urban driving, highway driving, nd stop-start, low-speed delivery service conditions. In addition, the impact of uch hybrid vehicle use on vehicle-related exhaust emissions is determined, and he ability to accommodate a different energy resource base in the longer term s evaluated, i.e., by permitting a portion of the recharge energy for the on-board nergy storage device (battery or flywheel) to be provided by wall-plug electric ower from the utility industry instead of from the on-board heat engine. Alternaive paths for power transmission from the heat engine to the vehicle drive wheels re considered along with the potential of regenerative braking to reduce vehicle nergy consumption.

his first of four volumes constitutes a summary of the more significant results f the study.

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PREFACE

This four-volume report presents the results of an analysis conducted by The Aerospace Corporation for the U.S. Department of Transportation, Transportation Systems Center, as part of the Automotive Energy Efficiency Project, sponsored by the Energy and Environment Division of the Office of the Secretary, U.S. Department of Transportation.

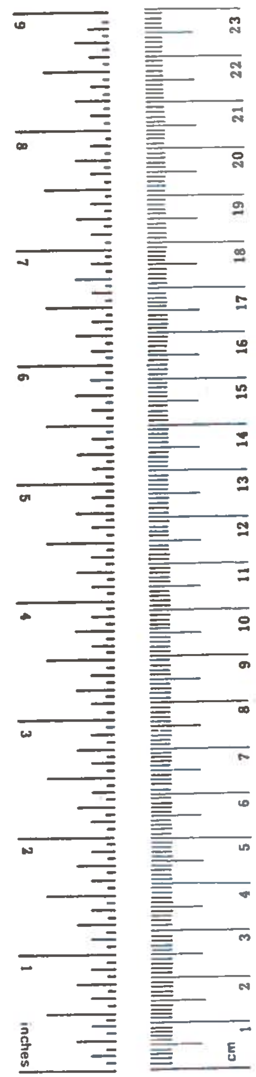
Appreciation is hereby extended to the Technical Monitor at the Transportation Systems Center, Mr. Joseph Abbas, whose guidance and suggestions were most helpful to the conduct of the study.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

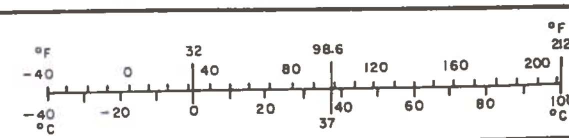
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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S.1 OVERVIEW AND SYNOPSIS OF FINDINGS

S.1.1 FUNDAMENTAL STUDY CONSIDERATIONS

The overall study objective was to provide a clear indication as to what forms of hybrid vehicles* could contribute to near-term (1980 to 1990) reductions in transportation energy consumption under a given set of operational conditions (i.e., determine if there is a role for hybrid vehicles in some application and whether they have a clear-cut advantage over other vehicles). A 2500-lb car, a 4000-lb car; and a 6000-lb delivery van was reviewed in this regard.

The hybrid vehicle designs examined in this study included those that allow for changes in how the energy storage system is recharged. By using recharge power from an electric outlet that is supplied by a stationary electric generating plant in addition to (or in place of) recharge power from the onboard heat engine, nonpetroleum-based fuels can be consumed for supplying vehicle propulsion energy needs. (Earlier studies had considered only the case of the onboard heat engine providing all recharge energy.) This means that coal or nuclear fuel sources could be used to supplant some of the gasoline consumed by the heat engine. Hence, the heat engine power setting could be varied uniformly from a high value that ensures all recharging by the heat engine to a low value where all recharging is accomplished by power from the electric outlet. Of course, as greater reliance is placed on the electric outlet, the hybrid vehicle operating range is decreased until it is operating almost as an all-electric or all-flywheel system.

The approach selected for evaluating hybrid vehicles was to use component performance maps to analytically model the vehicle powertrain operation for urban, highway, and stop-and-go driving situations. Following a thorough review and summary of documented powertrain component characteristics, a computer program was developed to calculate vehicle-related energy consumption and exhaust emissions of hybrid spark-ignition,

---

*Those vehicles that use a powertrain combining a heat engine with an energy storage device (e.g., battery or flywheel) for transmitting power to the vehicle drive wheels.

reciprocating piston, heat engine/battery and heat engine/flywheel systems. Computer results for hybrid vehicles were then compared with energy consumption characteristics of equivalent-weight, conventionally powered automobiles and with federal exhaust emission standards for 1975-76 model year light-duty vehicles.

The findings presented herein are considered to be a realistic technological appraisal of expected performance for the particular forms of hybrid vehicles examined; they are not intended to be a distillation of characteristics for all of the varied hybrid designs proposed by vehicle propulsion system designers. Indeed, the particular engine selected for use in the analysis, the particular means of powertrain operation, and the particular baseline references used for energy consumption and exhaust emissions must be recognized as having an influence on the present investigation.

Additional improvement in the powertrain of conventionally powered vehicles would also impact the study findings. The possible use of a continuously variable transmission, for example, could result in a marked improvement in conventional vehicle powertrain efficiency, reducing the fuel energy consumption, and, thereby, diminishing the relative potential advantage of hybrid vehicles. However, energy recovery by regenerative braking, and the ability to derive propulsion energy from stationary electric generating plants would continue to be unique features of hybrid vehicles that can assist in reducing energy consumption or aid in transferring transportation energy needs to less critical resources.

S.1.2 TECHNOLOGICAL CONSTRAINTS

Powertrain component characteristics used in the analysis were derived for systems estimated to be available as manufactured hardware in the near-term period of 1980 to 1990. The lead time available should be adequate for design, component test, and system prototype evaluation phases of a first-generation hybrid vehicle development program.

The most significant problem areas identified are related to the energy storage system, and they involve packaging, parasitic losses, and the efficient acceptance of regenerated braking energy. In hybrid electric vehicles, the battery system* has an imposed requirement for very high

*Nickel-zinc batteries were used in the analysis.

specific power (100 to 200 W/lb) without severely compromising specific energy (Watt-hour per pound). This is brought about by the limited power-train weight available, combined with the high power levels needed for vehicle acceleration. Reduction of the required specific power can be accomplished by reducing vehicle peak acceleration and cruise speed performance specifications along with efforts to reduce the weight of other elements in the powertrain.

Another battery problem lies in its limited ability to accept recharge in high-power bursts without large losses. The need for this form of charge acceptance is related to vehicle designs relying on regenerative braking to reduce energy consumption. Hybrid heat engine/battery systems, in contrast to all-electric systems, operate for the most part with batteries at a fairly high state-of-charge. This condition is considered very restrictive to acceptance of sustained high-power recharge energy.

From a weight standpoint, flywheel systems can be readily accommodated in the hybrid powertrain. The packaging problem resides in space restrictions. Within the physical limitations of the automotive chassis, and with the necessary adjuncts of guard ring, vacuum housing, and vacuum pump, the flywheel system energy storage capability is very limited, even for units that exceed 40,000 rpm. At best, it appears that the specific energy for flywheel systems with steel rotors* is only about 15 percent of the battery system. For hybrid systems where the onboard heat engine provides all recharge energy, the specific energy is a minor factor. It is only of significance in providing acceptable operating range for a vehicle that relies fully, or partially, on recharge power from an electric outlet.

A more serious problem with flywheels lies in the area of parasitic losses. These are losses related to high-speed rotor aerodynamic drag, rotor shaft support bearing drag, vacuum chamber seal losses, and power required to operate the vacuum pump. Low pressure in the flywheel housing will reduce the rotor drag, but pump power must increase accordingly. More extensive sealing of the vacuum chamber to reduce pump power requirements can lead to greater losses. The problems are magnified at the

*The primary system selected for study.

high speeds required for ensuring maximum possible energy storage with rotors made from reinforced plastic materials. Bearing drag losses could increase if additional rotor support is required for the automotive operating environment.

When compared with batteries, flywheels have far less limitations in regard to rapid acceptance of recharge energy from regenerative braking. The critical link in the power path for the configuration evaluated is actually the continuously variable, power-splitting, hydromechanical transmission, not the flywheel. At present, there are insufficient data to offer insight into what additional transmission refinements (e.g., gearing, clutching, fluid cooling) are required to provide for the needed reverse of power flow during regenerative braking and what impact this could have on transmission weight, volume, and efficiency. Outside of this consideration, it appears that only noise, produced by the high-pressure fluid, would be a possible technological constraint on early introduction of this system.

Power flow in electric drive motors is reversible, so that during regenerative braking they will act as generators. Separately excited motors have been favored for this purpose. The problem that remains is to be able to pass power efficiently under these conditions and then to be able to retain an efficient, high-speed, and lightweight unit for use during normal positive traction required for vehicle acceleration or forward speed maintenance. The design of an adequate, compact, cooling system would seem to be a major factor in achieving this result.

Experience with electric vehicles should alleviate potential problems in application of electric drive motors and power-conditioning equipment to hybrid heat engine/battery vehicles. Additionally, generators are not considered to be of any concern in the powertrain. The control system, however, is unique and will require considerable design and test effort for both battery and flywheel hybrid systems to ensure development of a stable, efficient, low-cost, reliable device.

No major problems are expected with the heat engine. Rather, the restricted form of operation proposed for its use on hybrid vehicles could possibly result in improved efficiency and aid in simplification of emission control systems, particularly if an engine were designed specifically for hybrid vehicles. But this type of operation is unique and test data might be required to validate expected lifetime and reliability.

The basic heat engine problem to be addressed is one of packaging. A compact, lightweight design is needed so that, in concert with other elements of the powertrain, the weight and volume limitations of automotive vehicles can be met. This generally precludes consideration of Rankine, Stirling, and diesel engines (although new, lightweight designs for the latter two engines might be deserving of further examination). The gas turbine and spark ignition engines would seem best suited to this role. In lieu of a comprehensive performance map depicting fuel consumption and emissions for an automotive gas turbine, the spark ignition engine was chosen for use in the present analysis.

Although not a design problem, the major constraint identified for heat engines was one of the specific relationships to be used for power as a function of rpm in an operating schedule. Once a given application for the hybrid vehicle has been established, then the schedule selection can be initiated. The tradeoff involved is simply fuel consumption versus oxides of nitrogen (NO_x) emissions. It will be found that energy savings are limited by the need to meet the federal emission standard for NO_x (or those variances agreed upon for California). Hydrocarbon (HC) and carbon monoxide (CO) emission standards are easily met.

S.1.3 VEHICLE DESIGN AND PERFORMANCE CONSIDERATIONS

This section discusses briefly the trends that evolved from parametric analyses conducted in this study. The intent was simply to ascertain the general impact on vehicle-related energy consumption and emissions of modifications to basic hybrid vehicle design and performance factors. It is not intended as a guide to vehicle designers. Each specific design should be analyzed separately to arrive at an efficient, reliable "best" system.

Vehicle-related exhaust emissions and energy consumption both increase substantially with vehicle loaded weight. On a relative basis, this consideration is maintained for exhaust emissions because the basis of comparison is a fixed set of standards. For energy consumption, however, the basis of comparison is not fixed; but rather it is the varying energy consumption of conventionally powered vehicles. The result, then, is that for a given class of vehicle (e.g., automobiles) a heavier hybrid vehicle can save more energy than a lighter hybrid vehicle when the savings is related to the energy used by equivalent weight conventionally powered vehicles. A deviation to this trend is noted for the delivery van because of its large aerodynamic drag when compared with the equivalent weight automobile. (Application of the basic trend to delivery vans would be expected if reference data were available for energy consumption of conventionally powered vans.)

Vehicle design peak cruise speed has a noticeable impact on both energy consumption and emissions. The higher design speeds result in greater energy consumption but reduced emissions, although the effect on energy consumption is quite small for the heat engine/flywheel hybrid vehicle. The other impact of higher cruise speed is to increase the design weight and volume of power transfer elements in the vehicle and thereby reduce the weight and volume available for the energy storage system in powertrain designs of fixed weight.

The impact of vehicle design peak acceleration was not of significance with regard to energy consumption or exhaust emissions. Its primary influence was to increase powertrain component weight and volume, producing the same impact on the energy storage system as high cruise speed. Indeed, the combined effect of increases in design cruise speed and acceleration can have a substantial effect on weight and volume allowance for the energy storage system.

Because of its improved efficiency in transferring power from the heat engine to the vehicle drive wheels, the parallel powertrain configuration uses less energy than the series configuration, providing there is no need to alter the onboard heat engine operating schedule. If further analyses show that the flexibility in the engine power/speed profile is compromised with the parallel design, then in certain vehicle applications the reverse may be true, and this configuration may prove to be a greater energy consumer than the series design.

Barring cost and design complexity factors, the most clearly defined advantage of hybrid vehicles over conventionally powered vehicles is the potential for recovery of vehicle kinetic energy by regenerative braking and subsequent storage of this energy in the battery or flywheel system. The fraction of energy expended at the vehicle drive wheels that can be recovered in the storage system is governed by the type of driving required of the vehicle, the size and weight of the vehicle, the powertrain efficiency between the drive wheels and the energy storage system, and the ability of the storage system to accept the energy. Nevertheless, whatever energy can be recovered is currently being wasted in vehicle braking systems and not being used to reduce fuel consumption. As an example, if about 15 percent of drive wheel energy can be recovered in the battery storage system, then vehicle fuel energy consumption can be decreased by as much as 20 percent for the parallel configuration. This result applies to a vehicle design operating range comparable to that for conventionally powered vehicles (about 350 miles). Greater savings would be possible at reduced design range.

Increased reliance on electric power (supplied by stationary electric generating plants) for recharging the energy storage system has a beneficial effect in terms of reducing energy consumption and NO_x exhaust emissions. The penalty for these benefits is a reduction in vehicle design operating range. Because of its superior energy storage capability, the impact on range of heat engine/battery hybrids is less than on heat engine/flywheel hybrids.

Parametric analyses showed that hybrid vehicles are sensitive to changes in powertrain design and efficiency. To attain the energy saving potential discussed in this report, particular emphasis would have to be placed on verifying in laboratory and road tests the powertrain component efficiencies used in the present analysis. For example, the analysis showed that a 1 percent change in efficiency could mean a corresponding 1 percent change in fuel energy consumption and an even greater percentage change in exhaust emissions. In addition, gear ratios between various power delivery and transfer units must be carefully selected to ensure that each unit does not operate for long periods under high loss/low efficiency conditions. These considerations are particularly of concern for vehicles that are intended for use in a variety of transportation applications.

S.1.4 APPLICATION POTENTIAL OF HYBRID VEHICLES TO THE PERSONAL TRANSPORTATION SECTOR

The various analyses conducted in this study have shown that, while meeting federal emission standards in urban driving situations, significant savings in fuel energy consumption are possible for hybrid vehicles when contrasted with conventionally powered vehicles. The system with the potential for the greatest savings is a parallel powertrain configuration capable of energy recovery by regenerative braking. Depending on the amount of energy recovered, design compromises may be required in vehicle operating range, peak cruise speed, and weight to achieve a given energy savings.

For urban driving applications characteristic of the federal tests used to ascertain light-duty vehicle compliance with emission standards, energy savings of about 15 percent are possible for hybrid heat engine/flywheel vehicles with large operating range and no regenerative braking. These savings can increase to 25 percent with 15 percent regenerative braking energy recovery. Similar savings are available for hybrid heat engine/battery vehicles with an operating range of about 100 miles. Even greater savings are possible for the heat engine/battery system at 75 miles range where 30 percent savings are shown for 15 percent regenerative braking energy recovery.

The greatest energy savings possible are in the application of hybrid vehicles to stop-and-go driving situations characteristic of certain types of delivery services (e.g., mail or milk delivery in residential neighborhoods). Such savings can be as large as 50 percent in fuel energy consumption, even without regenerative braking. Under these conditions, the conventionally powered reference vehicle is found to operate at a distinct disadvantage with very poor overall powertrain efficiency.

For sustained highway driving with speeds ranging from 45 to 60 mph, little, if any, energy savings are possible with the hybrid vehicle. This results from the fact that the powertrain of the conventionally powered vehicle is operating near peak efficiency and regenerative braking does not aid the hybrid system in this driving mode.

The energy savings discussed thus far are for all fuels used for vehicle propulsion [i. e., gasoline in the heat engine onboard the hybrid vehicle, and the various fuels used at stationary electric generating plants (coal, oil, gas, nuclear)]. Because the hybrid heat engine/battery vehicle can rely on power from electric generating plants, greater savings are indicated for petroleum-based fuels (oil and gas). As an example, for parallel configuration hybrid heat engine/battery vehicles with 15 percent regenerative braking energy recovery and with an operating range of about 100 miles in urban driving, almost 40 percent savings in these fuels are possible. The amount of petroleum-based fuels saved also depends on the region of the nation in which the heat engine/battery vehicle is used. In the Pacific Northwest, for example, power generation is almost entirely hydroelectric; therefore, this region could benefit most from the introduction of hybrid heat engine/battery vehicles. Propulsion energy normally supplied by the gasoline consumed by the onboard heat engine would now be supplied by a source that consumes virtually no fuel.

By contrast, to offer satisfactory design driving range, the heat engine/flywheel hybrid must operate with the heat engine providing just about all the recharge energy required. (The very small energy storage capacity of the flywheel compared with nickel-zinc batteries precludes any other form of operation.) Hence, there is no reliance on electric generating stations, and there is no geographic partiality governing introduction of the vehicle into the consumer market.

As a final consideration, it is of interest to contrast the hybrid vehicle to the all-flywheel or all-electric (battery) vehicle. As noted earlier, the energy storage capacity of the flywheel is much smaller than a nickel-zinc battery. Hence, in automotive applications, an all-flywheel version cannot provide any realistic personal transportation needs (operating range in urban driving would be only about 10 miles). However, an all-electric car capable of 80 mph cruise speed can achieve about a 60-mile range* in urban driving, using the same type of nickel-zinc batteries used

*The range can be improved to about 100 miles if acceleration and peak cruise speed are reduced to permit a reduction in motor weight that could be absorbed by installation of additional batteries.

in the hybrid vehicle. Furthermore, it can save about 40 percent in energy for all fuels when measured against the conventionally powered car. Up to 80 percent of petroleum-based fuel energy can be saved on a nationwide application. This is based on a national average figure for fuel energy needs of electric generating plants, showing that about 32 percent is presently provided by oil and gas.

For urban driving situations characterized by the EPA Urban Driving Cycle, a general picture that emerges shows the hybrid heat engine/flywheel system in all forms of powertrain configurations to be basically suited for a vehicle with large operating range requirements (> 100 miles), that will be capable of some degree of energy savings regardless of range, and that does not rely on recharging power from stationary electric generating plants. By contrast, the series configuration hybrid heat engine/battery system is more suited for use in a vehicle with short operating range requirements (< 100 miles), that can save more energy than the flywheel system, and that has major reliance on electric generating plants for recharge energy. This range restriction can be relieved if a parallel configuration design were to be used and, additionally, if an efficient regenerative braking energy recovery system is developed. These improvements to the powertrain would also aid in assuring that the vehicle can meet federal emission standards, particularly the critical NO_x standard.

At very short operating range (< 60 miles), the all-electric vehicle would be favored because of its relatively larger energy savings. Low performance all-electric vehicles have the potential to approach being competitive with high-performance hybrid heat engine/battery vehicles in regard to operating range and to provide even greater reductions in energy consumption and emissions when compared with conventionally powered vehicles. The tradeoff here is performance versus energy and emissions. The appropriate tradeoffs will reside with the vehicle designer who will require optimization studies to define physical and performance limitations and to aid in selection of a transportation vehicle design matched to the particular application.

The overall assessment is that on the basis of energy consumption, the more efficient heat engine/flywheel system uses less total energy than the heat engine/battery system. But not to be overlooked is the considerably greater energy storage capability of the nickel-zinc battery compared to that of the steel flywheel, allowing attainment of reasonable vehicle design range in urban driving when a major portion of recharge energy is derived from stationary electric generating stations. The heat engine/battery system can then have the potential for petroleum-based energy savings not available to heat engine/flywheel systems, because nationwide many of these generating plants rely on coal, nuclear, or hydroelectric energy sources (or could be converted to these sources) rather than oil or gas energy sources. Hence, the total energy consumed by the heat engine/battery system may be greater, but the petroleum-based energy consumed can be less.

Because petroleum-based fuels are presently the most critical resource for meeting nationwide transportation needs, the heat engine/battery system might be favored as the option for the near-term. All-electric vehicles would be even more strongly favored for conserving petroleum-based fuels, but, because of their present limited range, the applications would be much more limited than for the hybrid vehicle. Other alternatives, such as converting coal to petroleum products, must receive equal consideration in establishing future national energy conservation plans.

S.2 INTRODUCTION

Analyses and assessments were conducted for both heat engine/battery- and heat engine/flywheel-powered hybrid vehicles to determine if they could contribute to near-term (1980 to 1990) reductions in transportation energy consumption for several sets of operational conditions: urban driving, highway driving, and stop-start, low-speed delivery service. In addition, the impact of using these hybrid vehicles on vehicle-related exhaust emissions was determined, and the ability to accommodate a different energy resource base in the longer term was evaluated; i.e., by permitting a portion of the recharge energy for the onboard energy storage device (battery or flywheel) to be supplied by a stationary electric generating plant instead of from the onboard heat engine.

A sophisticated vehicle simulation model was used for the analyses. It included characteristic operational performance maps of major system components (e.g., heat engine, electric drive motor, battery, flywheel, transmission) and permitted observation of the critical interactions of system components under simulated driving conditions. These performance maps were based on a review and assessment of the current technological status of powertrain components. The impact of component performance limitations on vehicle performance was included in the hybrid system assessment.

Three vehicles were evaluated: a 2500-lb car, a 4000-lb car, and a 6000-lb van. The vehicle-related energy consumption and emissions of hybrid vehicles were compared with those of representative conventional spark ignition-powered vehicles manufactured to meet the federal emission standards for 1975-76 model year light-duty vehicles--HC = 1.5 gm/mi, CO = 15.0 gm/mi, NO_x = 3.1 gm/mi). "Vehicle-related" refers to the sum of energy (or of emissions) from the vehicle and from the electric generating plant used to supply power for recharging the hybrid vehicle energy storage device. Therefore, the fuel consumption and emission characteristics of both the generating plant and the vehicle were simulated. In addition, the vehicle simulation model was used to characterize the all-electric (i.e., all-battery) vehicle for limited comparative purposes.

The principal study results are summarized in this volume. Because of the many variables involved, the specific hybrid systems examined are defined and then the study results are presented as a function of hybrid vehicle propulsion system type.

S.3 HYBRID SYSTEMS EXAMINED

S.3.1 POWERTRAIN CONCEPTS AND CONFIGURATIONS

The hybrid powertrain has been proposed as a propulsion method for conserving petroleum-based fuel by virtue of the concept that, if the energy storage device can meet the rapidly fluctuating propulsion power demands, the heat engine can be effectively divorced from these demands and run at the most efficient operating point. The specific form of hybrid vehicle addressed in this study combines an on-board heat engine with an energy storage system that is recharged by both the heat engine and by power from an electric wall outlet. Therefore, additional petroleum-based fuels can be conserved if the electric generating plant burns coal. The vehicle propulsion energy sources are then the fuels consumed by the heat engine and by the stationary electric generating plant that delivers power to the outlet. Interposed between these energy sources and the vehicle drive wheels, a variety of energy storage devices, power flow paths, and powertrain component combinations can be envisioned.

Energy storage devices selected for the analyses were limited to batteries and flywheels. The rationale for this selection is that only these devices were sufficiently characterized for automotive application by a complete, empirically derived operating map. Additional powertrain elements needed for power conversion were selected on the basis of: compatibility with these energy storage devices, good efficiency, and operating flexibility.

Hybrid powertrain concepts can be grouped by the flow paths used to transmit power to the vehicle drive wheels. The resulting two classes -- series configuration and parallel configuration -- are shown in Figure S-1.

The first class, series configuration, is characterized by the principle that energy flowing from the heat engine to the rear wheels must first pass through multiple intermediate energy conversion devices. This means of decoupling the engine from the rear wheels provides a large

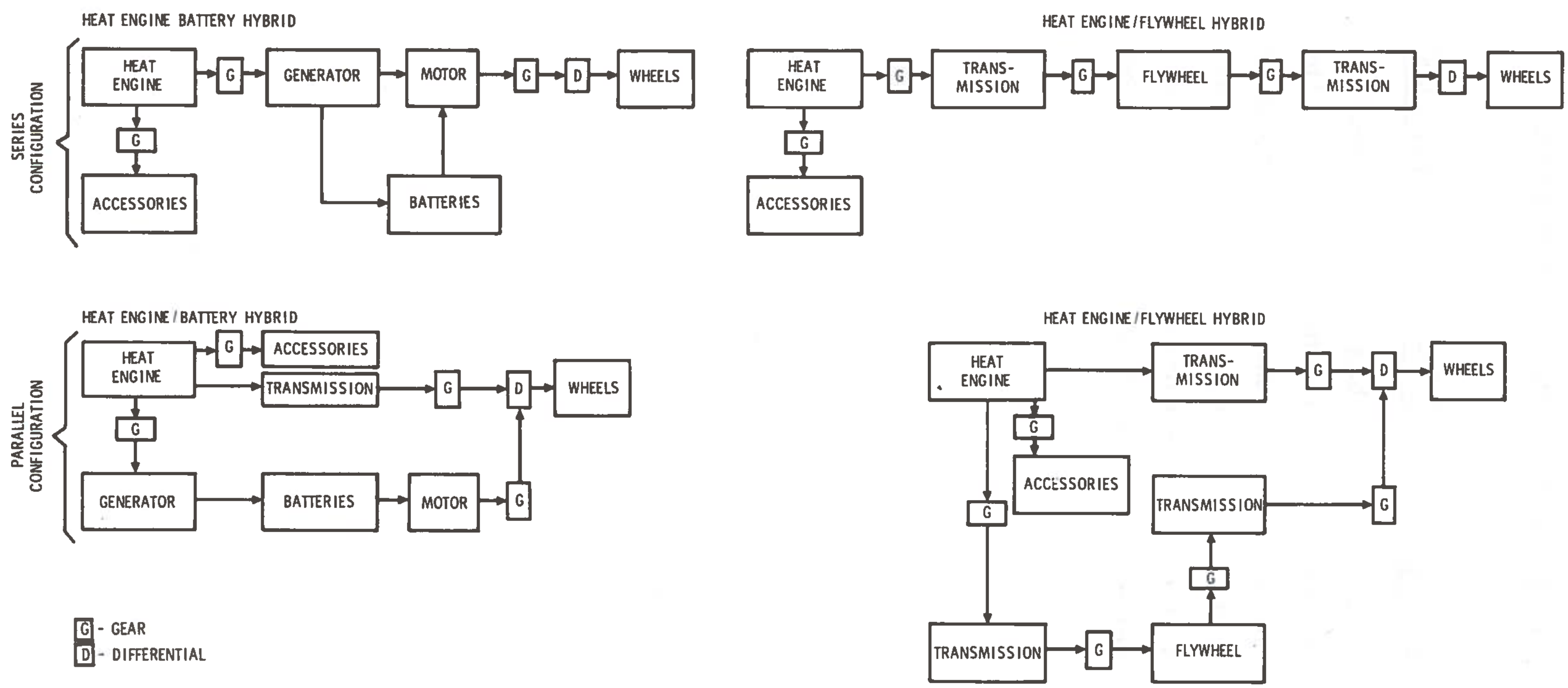


FIGURE S-1. HEAT ENGINE HYBRID VEHICLE POWERTRAIN CONCEPTS degree of flexibility in selecting engine operating modes that offer the potential for reducing fuel consumption and exhaust emissions.

In the case of a series-configured heat engine/battery hybrid, the heat engine drives an electrical generator that transmits energy to the electric drive motor and thence to the wheels. A portion of the generator energy is directed to recharging the batteries as needed. For a series-configured heat engine/flywheel hybrid, the heat engine drives the flywheel through a transmission and the flywheel drives the rear wheels through an additional transmission.

The second class, parallel configuration,* is characterized by the principle that a portion of energy flowing from the heat engine to the rear wheels passes through only one energy conversion device. This coupling to the rear wheels is somewhat more limited in terms of engine flexibility than for the series configuration, but the power transmission losses are less and the overall system efficiency is higher if heat engine efficiency [brake specific fuel consumption (BSFC)] is maintained at levels equivalent to that of the series configuration. Furthermore, some of the non-energy-storing components that are driven by the engine in the parallel configuration are required to supply acceleration power only; whereas in the series configuration they are required to supply cruise plus acceleration power. Hence, in some cases, the size and weight of components in the parallel configuration can be reduced from those for the series configuration. An example of this effect occurs in the heat engine/battery hybrid where the electric drive motor (which can operate at three to four times rated power for brief acceleration periods) can be markedly reduced in size.

For a parallel-configured heat engine/battery hybrid, heat engine power in one of the two parallel energy flow paths drives a generator to recharge the batteries that are used to provide acceleration power to an electric motor that is differentially geared to the heat engine drive shaft. Similarly, for a parallel-configured heat engine/flywheel hybrid, heat

*This term was originally used for hybrid heat engine/electric systems to denote the parallel flow of mechanical and electrical energy to the rear wheels. The broader definition as used herein is necessary because of application of the term to heat engine/flywheel systems.

engine power in one of the two parallel energy flow path drives a flywheel through a transmission; the flywheel then delivers power to the heat engine drive shaft through a transmission and differential gear system. In the other parallel branch of both systems, the engine also delivers power directly to the rear wheels through a transmission linked to the differential.

S.3.2 ENGINE OPERATING MODES

Different operating modes have been considered for the hybrid vehicle. Several designs are based on the unimodal hybrid concept, whereby a portion of the heat engine energy is used continually to replace all or a portion of energy drained from the onboard energy storage device (battery or flywheel). Other designs have resulted in a form of trimodal operating scheme whereby the vehicle can be driven alternatively in (a) the hybrid mode (onboard engine driving and recharging), (b) the battery-alone (or flywheel-alone) driving mode, or (c) the engine-alone driving mode. A somewhat simpler version of this design is the bimodal operating scheme whereby the vehicle is driven only in a battery-alone (or flywheel-alone) mode or an engine-alone mode. For this case, the vehicle would normally be driven in the battery (or flywheel) mode with recharging provided by a source external to the vehicle; the engine is then used merely to extend vehicle operating range whenever required.

The method of engine operation selected for use in analysis of the hybrid powertrain is a more difficult choice than that of the powertrain configuration. Generally speaking, fixing power and speed would offer two advantages. First, the engine could be run near its most efficient operating point. Second, if a new engine were designed, considerable simplicity would be expected to result. However, for the heat engine/battery hybrid, fixed conditions imply an engine setting at large power levels to avoid extensive energy extraction from the less efficient battery (for example, during vehicle high-speed cruise). An engine operating in this manner would waste considerable fuel during vehicle deceleration and stopping. Alternatively, the unknown factors influencing system lifetime and control system complexity preclude selection of on-off operation at this time. Hence, as a compromise, the following approach is carried on in this study. (For consistency, the heat engine/flywheel system is operated in the same manner.)

In essence, power at the generator (or flywheel) output is maintained at a fixed value up to a given vehicle speed. Figure S-2 illustrates this power variation. The shift from fixed power takes place only when the vehicle road load as determined by the generator output (for battery system) or by the engine transmission output (for flywheel system) exceeds the fixed power level. Then the generator (transmission) power output is increased and simply follows the increasing road load requirement as vehicle speed increases. At the fixed power setting of the generator (transmission), the heat engine power and speed are essentially fixed; they would vary slightly if the generator efficiency varies (due to load changes) in the case of the battery system, or if the transmission efficiency varies (due to flywheel speed changes) in the case of the flywheel system.

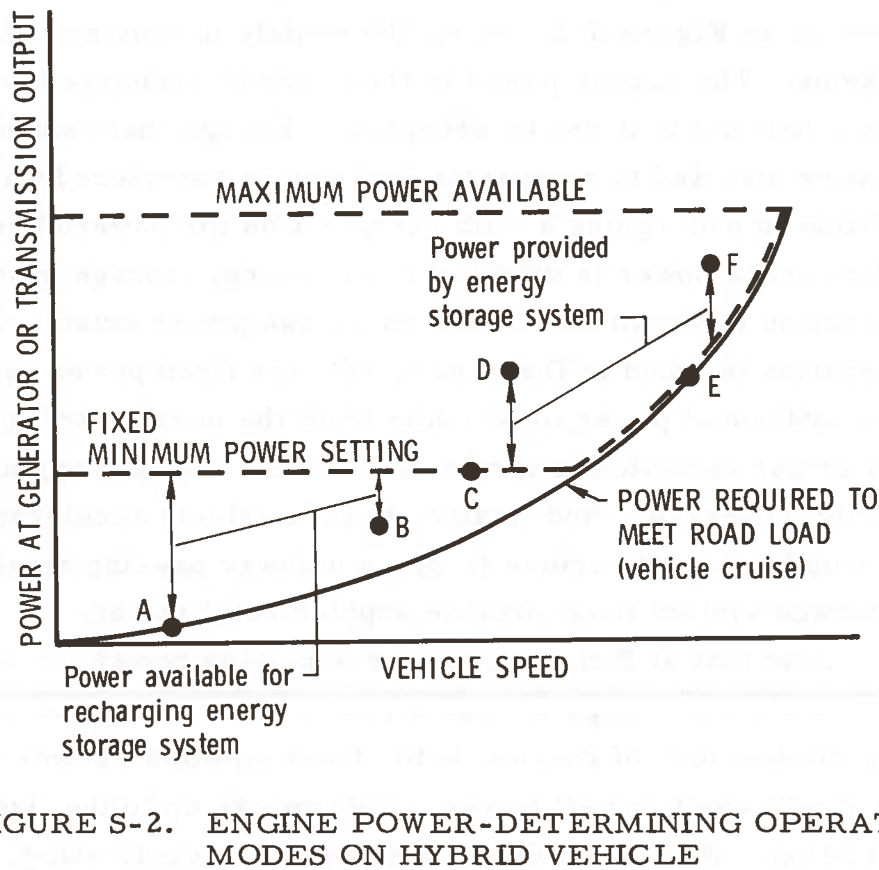


FIGURE S-2. ENGINE POWER-DETERMINING OPERATING MODES ON HYBRID VEHICLE

For any required engine power output, engine speed is established by the operating constraint of fixed intake manifold pressure. The manifold pressure selected was based on achieving a reasonable balance between fuel consumption and NO_x emissions (i.e., achieving an operational condition that permits the vehicle to meet federal emission standards while competing with or bettering the fuel consumption of conventionally powered vehicles). The particular schedule of engine speed and power that resulted was maintained irrespective of vehicle design or driving cycle. Obviously, some improvement in engine fuel consumption could be accomplished if the schedule were revised to cause the engine to operate at best fuel consumption for those driving cycles that are not constrained by the need to meet federal emission standards.

The various vehicle power demand situations are noted by letter designation on Figure S-2. At A, the vehicle is moving at low-speed cruise conditions. The excess power is then used to recharge the energy storage system (assuming it can be accepted). Energy that cannot be accepted must be diverted to a separate load and is considered wasted. At B, the vehicle is undergoing a mild acceleration (or powered deceleration) and again, the excess power is directed to the energy storage system. A higher acceleration is shown for C, and no excess power exists. An even higher acceleration is found at D and now, with the fixed power setting exceeded, the additional power must come from the energy storage system. A high-speed cruise condition is shown at E, where the heat engine output was necessarily increased. And finally, at F, a vehicle acceleration is called for during high-speed cruise (e.g., a highway passing maneuver) and the energy storage system must provide supplemental power.

Note that at B the engine was supplying power for vehicle acceleration without any change in engine power output or engine speed. This effect is diminished, of course, if the fixed minimum power setting is reduced, but it will apply for all power requirements up to the fixed minimum power setting. When the vehicle is stopped or decelerating, the generator (transmission) power output is also kept fixed (unless it is experiencing a high-speed powered deceleration). If the energy storage system is fully charged, some energy savings would be possible if the engine were throttled back to an idle condition. This degree of sophistication, however, was not introduced into the computer program model of the hybrid power-train. Indeed, it would prove somewhat more difficult to achieve for the flywheel system because the direct mechanical linkage provided by the transmission would require a declutching mechanism.

In regard to recharge energy from the electric outlet, it was assumed that this was accomplished only at the end of a given driving period. For the battery system, this is advantageous because a depleted battery can accept higher recharge currents than a battery near a full state of charge. Hence, less recharge energy from the electric generating plant is wasted. However, achievement of maximum vehicle acceleration may be marginal with a heavily depleted battery (this situation can be expected when the electric outlet provides the major portion of recharge energy). Of course, manual override of the programmed engine operation could provide high-power, onboard recharge at driver option if a series of maximum accelerations were contemplated.

S.3.3 DRIVING CYCLE CHARACTERISTICS

Three types of driving cycles were selected for use in comparative evaluation of the hybrid vehicle with a conventionally powered vehicle. These cycles encompass a wide range of driving characteristics. The U.S. Environmental Protection Agency (EPA) Urban Driving Cycle characterizes driving in city traffic combined with driving on freeways. It is based on vehicle speed histories obtained in the City of Los Angeles, California, and is used by EPA for validating new car compliance with Federal Light-Duty Vehicle Emission Standards. Sustained high-speed driving is characterized by the EPA Highway Driving Cycle. Both the EPA Urban and Highway Driving Cycles are used to establish new car fuel consumption in miles per gallon. The U.S. Postal Service Driving Cycle is derived from a recent specification issued for purchase of a light-delivery electric truck. This cycle is considered herein to represent the driving characteristics of stop-and-go delivery service vehicles.

A velocity history for each cycle is presented in Figures S-3 through S-5. These cycles can be summarized as follows.

Driving Cycle	Distance (mi)	Time (sec)	Average Speed (mph)	Peak Speed (mph)
EPA Urban	7.45	1372	19.55	56.7
EPA Highway	10.2	765	48.0	60
U.S. Postal Service	0.542	228	8.6	20

S.3.4 HYBRID VEHICLE CHARACTERISTICS

Physical characteristics used to determine the road load of the three hybrid vehicles are given in Table S-1.

Maximum vehicle performance is specified by design peak cruise speed and design peak acceleration (designated by the time to reach 60 mph from a stop). These specifications are included in Table S-1. The design peak cruise speed is based on using only the heat engine for power to achieve this speed. Power augmentation from the energy storage system can permit a considerable increase in speed for short periods (e.g., passing another vehicle) subject to design speed limits for other powertrain elements (e.g., drive motor in the hybrid heat engine/ battery system).

Within the study guidelines, the vehicle design peak acceleration has essentially no effect on powertrain component efficiency levels during vehicle operation over any given driving cycle. However, the design peak cruise speed does impact the powertrain efficiency indirectly. This comes about because efficiency (i.e., BSFC) is a function of the engine operating condition expressed as percent of peak power output, and the peak power output is set by the design peak cruise speed. It should be noted that for a given design peak acceleration and cruise speed, the entire powertrain design was fixed, regardless of the driving cycle selected for vehicle evaluation.

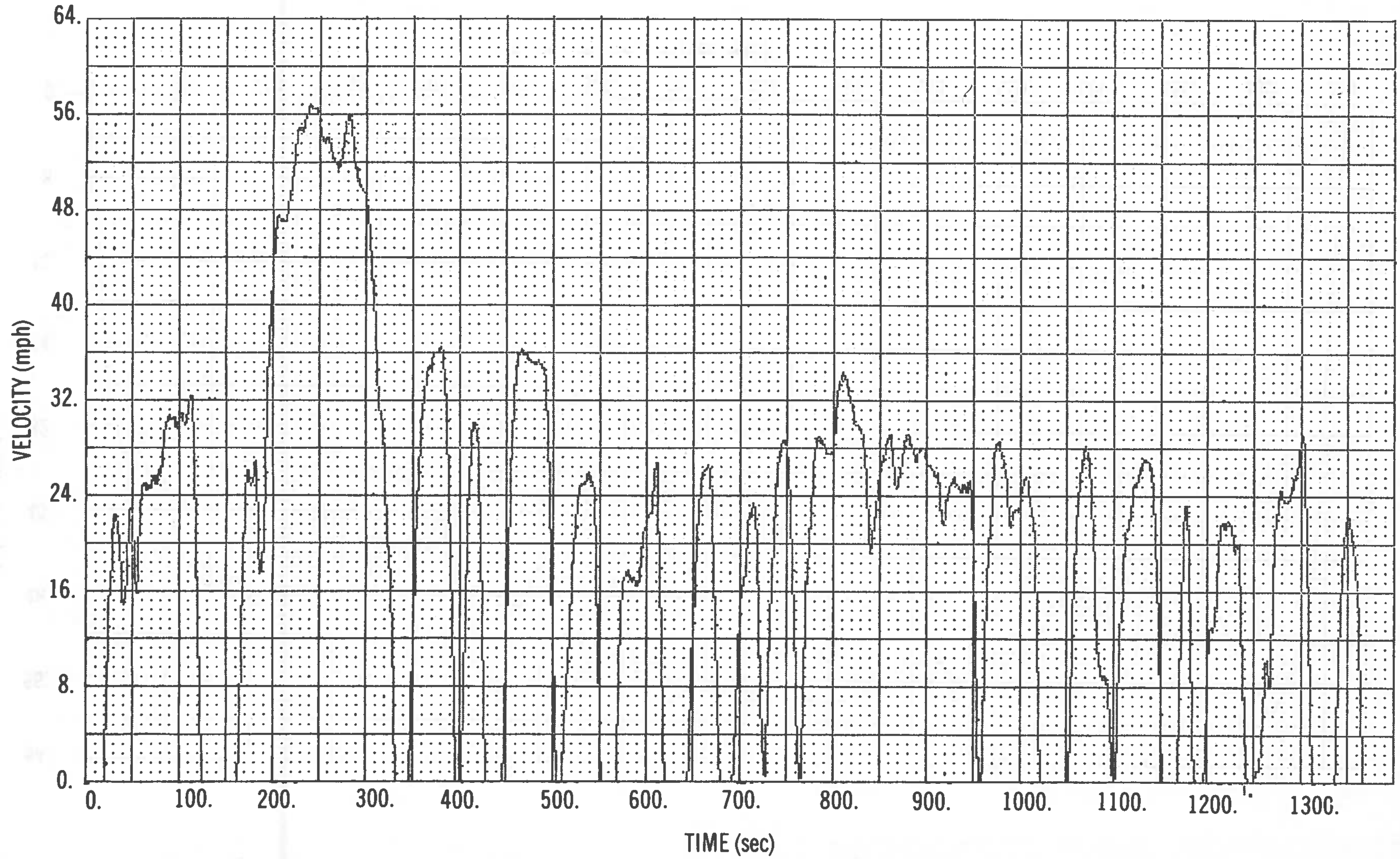


FIGURE S-3. VEHICLE VELOCITY HISTORY: EPA URBAN DRIVING CYCLE

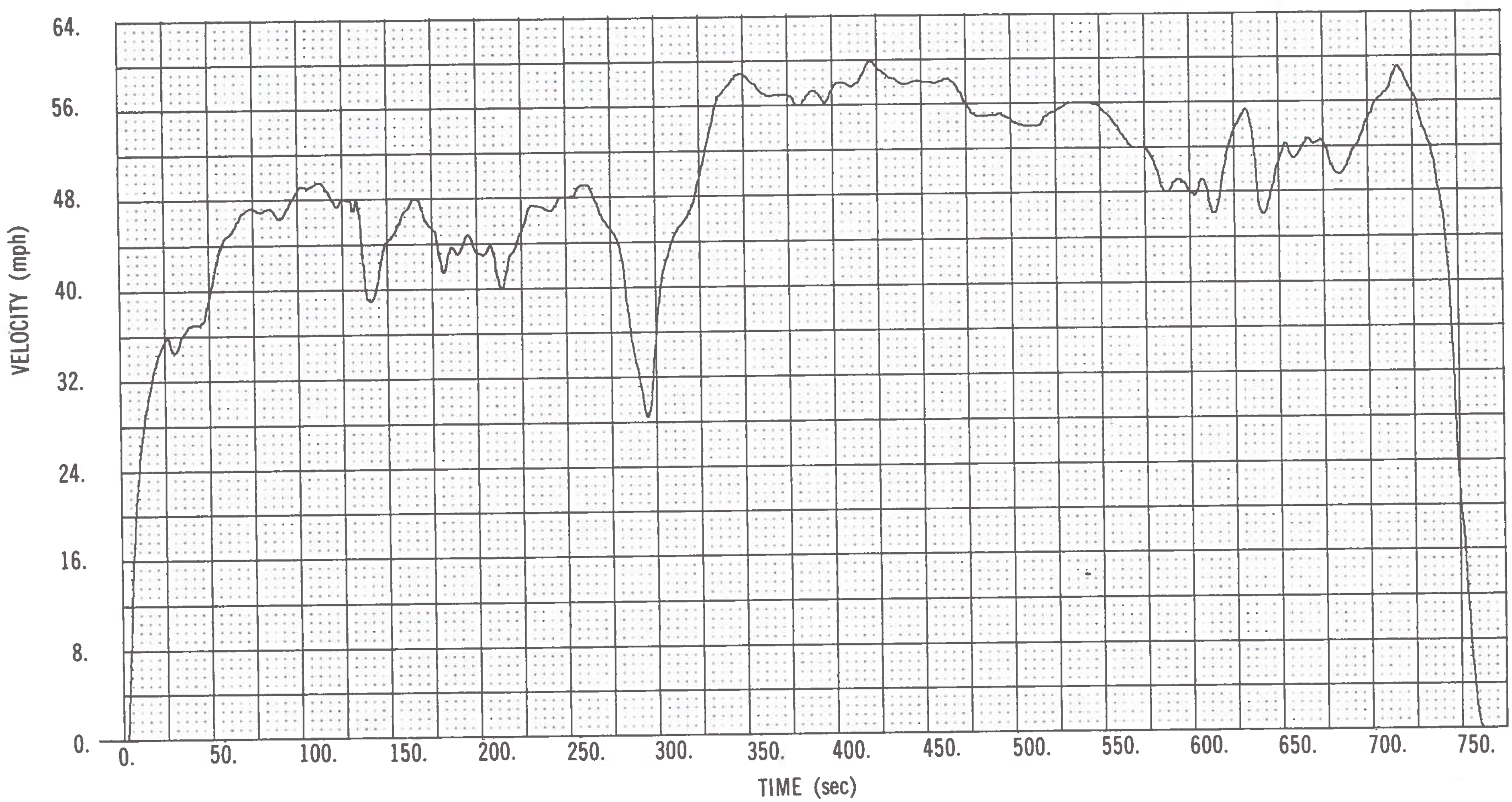


FIGURE S-4. VEHICLE VELOCITY HISTORY: EPA HIGHWAY DRIVING CYCLE

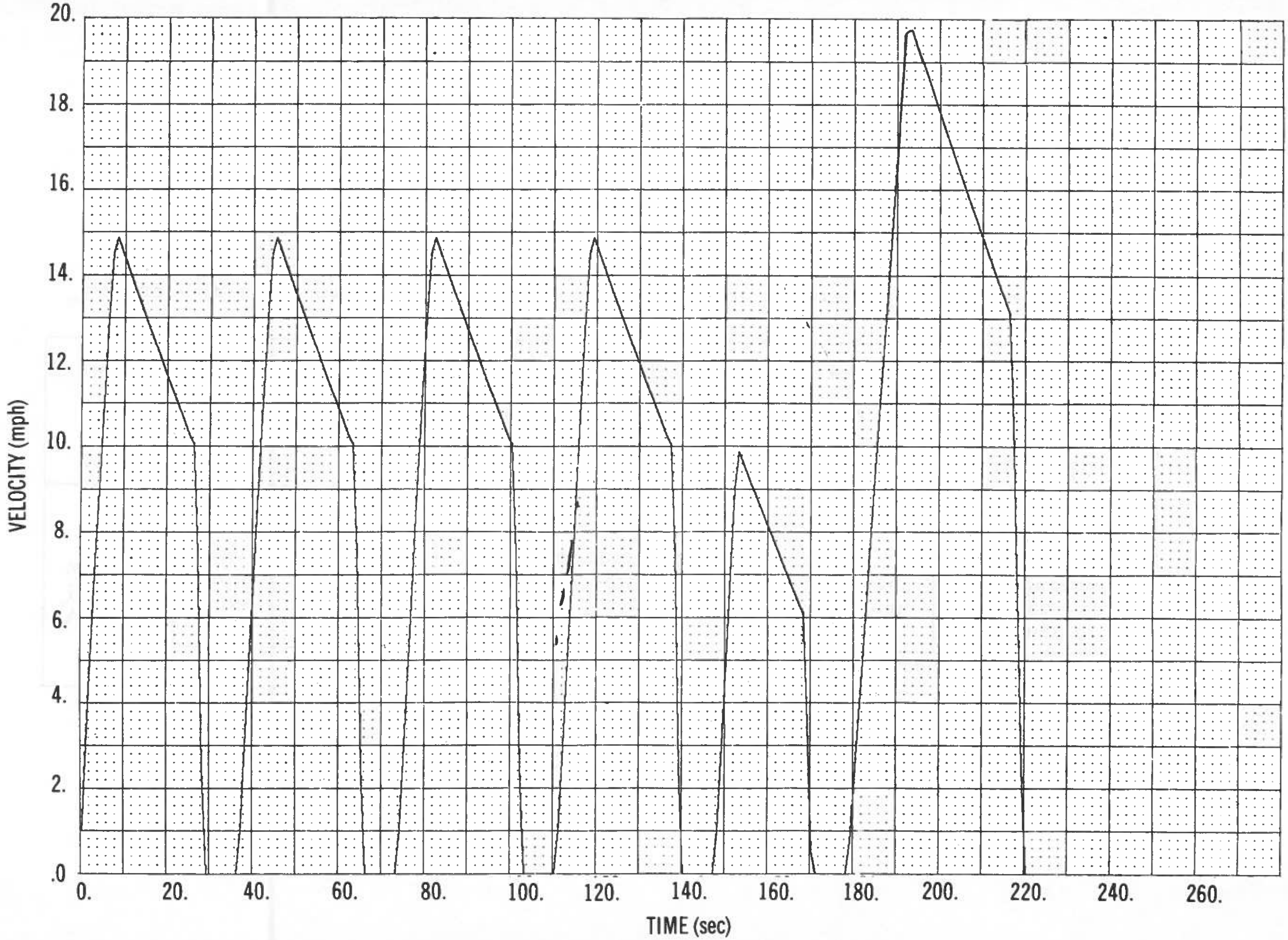


FIGURE S-5. VEHICLE VELOCITY HISTORY: U.S. POSTAL SERVICE DRIVING CYCLE

TABLE S-1. PHYSICAL AND PERFORMANCE CHARACTERISTICS FOR HYBRID VEHICLES

Vehicle Loaded Weight[a] (lb)	Physical Characteristics				Performance Characteristics	
	Tire Radius (ft)	Tire Pressure (psi)	Drag Area (ft^2)	Drag Coefficient (dimensionless)	Design Peak Cruise Speed (mph)	Range of Design Peak Acceleration, Time to Reach 60 mph (sec)
2500	0.98	25	19.0	0.45	65	11 to 20
4000	1.09	25	22.8	0.45	55, 65, 80	11 to 20
6000	1.215	40	35.0	0.76	65	21 to 30

[a]Loaded weight includes 300 lb for occupants and luggage in cars and 1000 lb for driver and payload in van.

S.3.5 CONVENTIONALLY POWERED (BASELINE) VEHICLE CHARACTERISTICS

The energy consumption and exhaust emissions of each hybrid vehicle are compared with those of the conventional vehicle in this analysis. The conventional vehicle is considered to be the domestic automotive product powered by a reciprocating piston, spark ignition engine and fueled by gasoline. For a given loaded weight, it was assumed that the physical characteristics (Table S-1) of the conventional vehicle and the hybrid vehicle were identical (including passenger and luggage capacity). With regard to performance characteristics, all conventional vehicles should be able to exceed 80 mph design peak cruise speed. Although acceleration times are variable and depend on the design rated engine power and vehicle weight, except for special performance vehicles, the times are certainly bracketed by the values given in Table S-1.

Energy consumption and exhaust emissions are the two most important characteristics for comparison. Energy consumption data for both the EPA Urban and Highway Driving Cycles were based on the average, sales-weighted gasoline mileage figures for 1975 model year vehicles tested on a chassis dynamometer by EPA. A vehicle simulation computer model was used to calculate gasoline mileage for vehicles operating on the U.S. Postal Service Driving Cycle.

Table S-2 shows the mileage figures for the three conventional vehicle weights analyzed in the present study and lists the conversion to equivalent energy in kilowatt-hours per mile of the fuel consumed by the engine.

The reference exhaust emissions are the federally mandated interim standards for 1975-76 model year light-duty vehicles: HC = 1.5 gm/mi, CO = 15.0 gm/mi, and NO_x = 3.1 gm/mi. These emissions apply only to the EPA Urban Driving Cycle; no emissions standards exist for the other cycles.

To determine vehicle operating range, the vehicle fuel economy in miles per gallon must be multiplied by the fuel tank capacity in gallons. Fuel tank capacities that were assumed for both hybrid and

TABLE S-2. FUEL ENERGY EXPENDITURE OF CONVENTIONAL VEHICLES

Vehicle Loaded Weight (lb)	EPA Urban Driving Cycle		EPA Highway Driving Cycle		U.S. Postal Service Driving Cycle	
	Mileage (mpg)	Energy Consumed (kW-hr/mi)	Mileage (mpg)	Energy Consumed (kW-hr/mi)	Mileage (mpg)	Energy Consumed (kW-hr/mi)
2500	21.7	1.56	31.0	1.09	12.4	2.72
4000	14.2	2.38	19.4	1.74	8.1	4.15
6000	9.3	3.64	14.1	2.40	5.3	6.34

conventionally powered vehicles and the range calculated for conventional vehicles are given in Table S-3. (Vehicle operating range for hybrid vehicles is discussed in Section S.4.1.4.)

S.3.6 HYBRID POWERTRAIN SYSTEM SIMULATION

The series configuration hybrid powertrain was examined in greatest detail. For the heat engine/battery hybrid it included: a conventional 1975 model year General Motors 140-cubic-inch-displacement (CID), 4-cylinder, spark ignition engine utilizing air injection, exhaust gas recirculation, and oxidizing catalyst for emission control; nickel-zinc storage batteries with specific energy density of 22 W-hr/lb; an ac electric generator; a series-wound dc drive motor; and a solid-state chopper control to regulate battery power to the dc drive motor. For the heat engine/flywheel hybrid it included: a conventional 1975 model year General Motors 140-CID, 4-cylinder, spark ignition engine; a 1.09-foot-diameter, 24,600 rpm, steel flywheel; continuously variable transmissions; and a control system to regulate power flow. The flywheel system included a guard ring, vacuum housing, and vacuum pump to support a pressure of 5 mmHg.

These powertrain configurations were characterized by scalable operational performance maps for the heat engine (including engine auxiliaries and vehicle accessories), battery, dc drive motor, flywheel, and transmission. The vehicles were operated over the EPA Urban and

TABLE S-3. FUEL TANK CAPACITIES FOR HYBRID AND CONVENTIONALLY POWERED VEHICLES AND RANGE FOR CONVENTIONALLY POWERED VEHICLES

Vehicle Loaded Weight (lb)	Assumed Fuel Tank Capacity (gal)	Conventionally Powered Vehicle Range (mi)		
		EPA Urban Driving Cycle	EPA Highway Driving Cycle	U.S. Postal Service Driving Cycle
2500	12.5	271	387	155
4000	20.0	284	388	162
6000	30.0	279	423	160

Highway Driving Cycles and the U.S. Postal Service Driving Cycle with the use of the vehicle simulation model. This simulation permitted observation of the critical interactions of components and the quantification of power flow in each major portion of the system.

Engine exhaust emission characteristics used in this study are for a warmed-up engine. Use of these data for determining vehicle emissions could be considered to be somewhat at variance with procedures required by EPA for determining vehicle emissions wherein a cold-soak period is required prior to emission measurements. Previous data have shown that engine choking during cold start has a marked effect on exhaust emissions during the first 60 seconds of the test cycle. Hence, ultimately some correction to the calculated hybrid vehicle emissions may be necessary. Since modern engines with shortened choke periods and fuel mixture preheating are designed for reduced impact of cold start on emissions, the correction might be quite small. In addition, engine choking required for conventional powertrains may be reduced or even eliminated for hybrid powertrains because: (a) the engine is not required to supply rapid changes in power level, (b) vehicle power could come from the energy storage system until the engine warms up, and (c) engine starting might be provided by delivery of power from the energy storage system without the need for introduction of fuel-rich mixtures.

Additionally, because the General Motors 140-CID engine was not designed for operation in a hybrid vehicle, changes to the spark timing, air-fuel ratio, and emission control system might also be warranted in an actual design if fuel consumption and/or emissions improvements could be shown by test data.

Subsequently, the magnitude and distribution of heat engine power in the series configuration was modified to permit separate determination of performance for the parallel configuration and for the application of regenerative braking. For the hybrid heat engine/battery parallel configuration, it was estimated that the heat engine output shaft energy (exclusive of battery recharge energy and engine auxiliary vehicle accessory drive energy) would be 70 percent of that required in the series configuration, regardless of driving cycle. This figure was based on the improved efficiency of an automatic transmission compared with the combined efficiencies of the generator/drive motor set. For the hybrid heat engine/flywheel parallel configuration the automatic transmission efficiency was fixed at 90 percent, and this was reflected in a variable impact on shaft energy ranging from 63 to 84 percent, depending on the particular driving cycle being considered.

Regenerative braking was treated parametrically. Ten and 15 percent energy recovery values were used for comparative purposes for the EPA Urban Driving Cycle, and 15 and 30 percent for the U.S. Postal Service Driving Cycle. (The characteristics of the EPA Highway Driving Cycle were not favorable to recovery of any significant amounts of energy by regenerative braking.) The percentage of energy recovery refers to the percentage of total driving cycle energy expended at the vehicle drive wheels that is recovered and delivered into the energy storage system by the regenerative braking system. This energy recovery amount was then used to reduce the energy required from the heat engine for recharging the energy storage system.

The vehicle-related energy consumption and exhaust emissions were calculated as a function of γ, the fraction of recharge energy that is provided by the onboard heat engine (or heat engine plus regenerative braking). For the case of no regenerative braking when $\gamma = 0$, all recharging is accomplished by power from an electric outlet (supplied by an electric generating plant); when $\gamma = 1.0$, all recharging is accomplished by power from the onboard heat engine. Intermediate values designate the division of recharging between these two energy sources.

To illustrate the above effects, Figure S-6 shows the distribution of heat engine shaft output energy over the EPA Urban Driving Cycle for the 4000-lb heat engine/battery hybrid car with the series configuration powertrain. Figure S-7 depicts the effect on heat engine energy required as the configuration is changed to parallel and as regenerative braking is added to both series and parallel powertrain configurations of the same 4000-lb car over the same driving cycle. In the case of regenerative braking, a γ of 0 is not possible, of course, because regeneratively stored energy always assures $\gamma > 0$, even if the heat engine portion of battery recharge energy is reduced to 0.

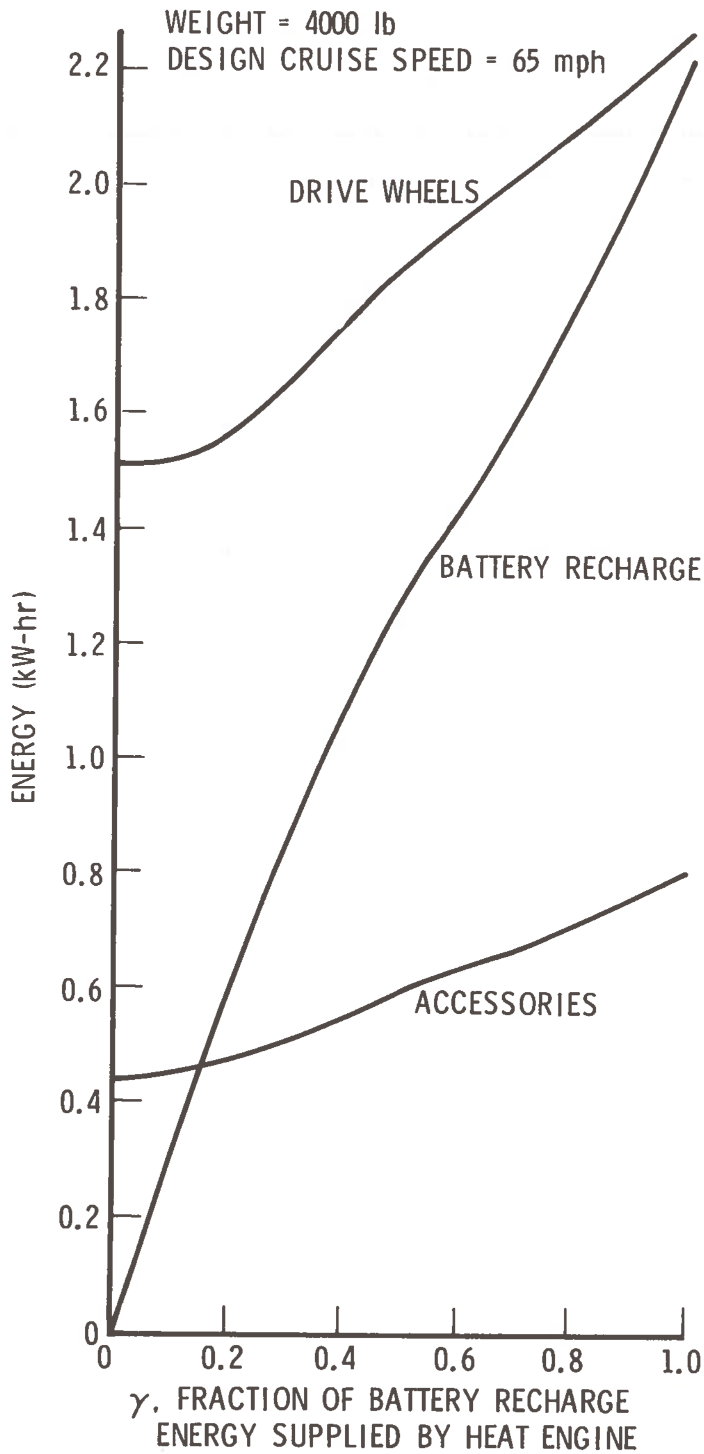


FIGURE S-6. HEAT ENGINE ENERGY DISTRIBUTION FOR HEAT ENGINE/BATTERY HYBRID VEHICLE: EPA URBAN DRIVING CYCLE, SERIES CONFIGURATION

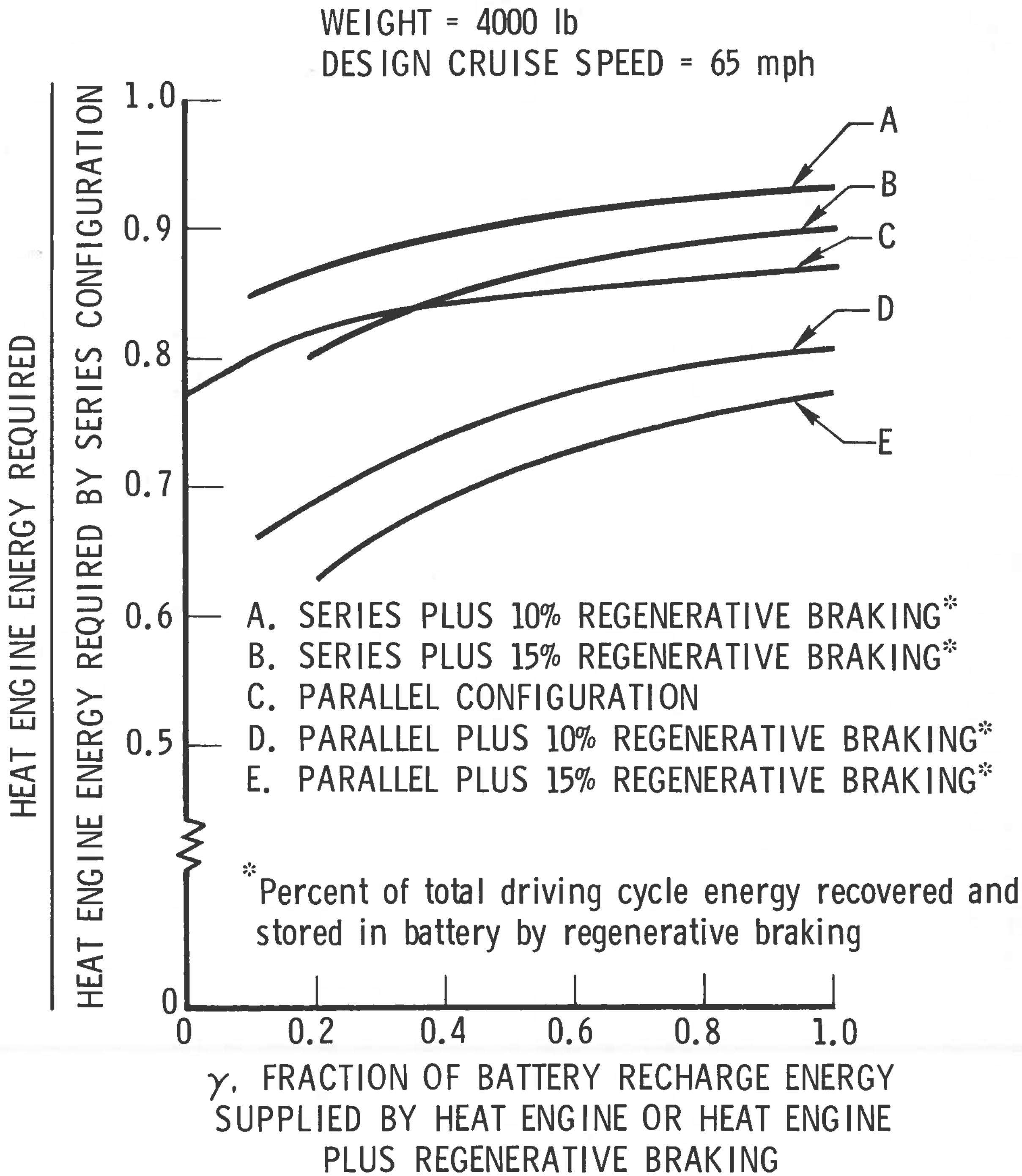


FIGURE S-7. IMPACT OF PARALLEL OPERATION AND REGENERATIVE BRAKING ON HEAT ENGINE ENERGY REQUIREMENTS FOR HEAT ENGINE/BATTERY HYBRID VEHICLE: EPA URBAN DRIVING CYCLE

S.4 HYBRID HEAT ENGINE/BATTERY SYSTEM RESULTS

Analysis results for various vehicle weights, powertrain configurations, and performance design criteria are presented as a function of γ. Additional factors discussed are regenerative braking, vehicle operating range, and impact of regional characteristics of electric generating plants.

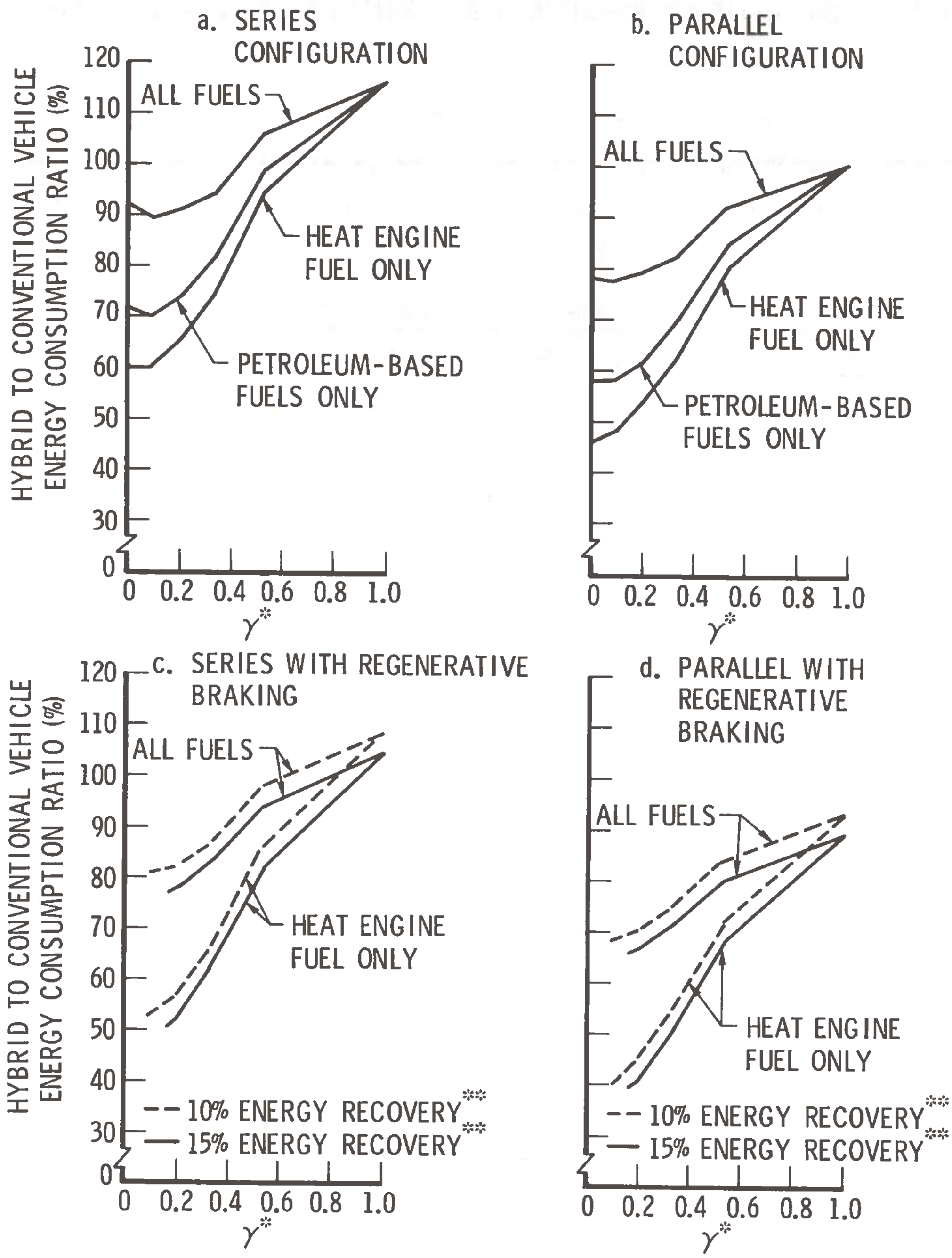
S.4.1 ENERGY CONSUMPTION CHARACTERISTICS FOR THE EPA URBAN DRIVING CYCLE

S.4.1.1 4000-lb Car

Figure S-8 illustrates the fuel energy consumption characteristics of the 4000-lb heat engine/battery hybrid vehicle when operated over the EPA Urban Driving Cycle. In all cases, the energy consumption of the hybrid vehicle is referenced to the gasoline energy consumption of the baseline conventionally powered vehicle operated over the same cycle (at 14.2 mpg or 2.38 kW-hr/mi, as shown in Table S-2).

As shown in Figure S-8a, the series configuration consumes approximately 16 percent more energy (and more tanked gasoline) if the heat engine is used to provide 100 percent of the battery recharge energy. As more electric outlet energy is used for battery recharge (as the heat engine fixed minimum power setting is reduced and γ becomes smaller), the fuel consumed by the heat engine is markedly reduced, with a lower level of 60 percent of equivalent tanked gasoline in the $\gamma = 0$ to 0.1 range. In this same γ range, the overall energy consumption of the hybrid (tanked onboard gasoline plus the recharge energy generated by fuel consumption at the electric generating power plant) is approximately 90 percent that of the reference baseline vehicle or approximately a 10 percent savings in total fuel energy consumption. The leveling out of energy consumption below $\gamma = 0.1$ for the heat engine is the result of a reduction in engine efficiency found at low power output such that about the same (or slightly more) fuel is expended at the power setting corresponding to $\gamma = 0$, as the higher power setting for $\gamma = 0.1$. This same characteristic can also be seen in Figures S-9 and S-10 for the 2500-lb and 6000-lb vehicles.

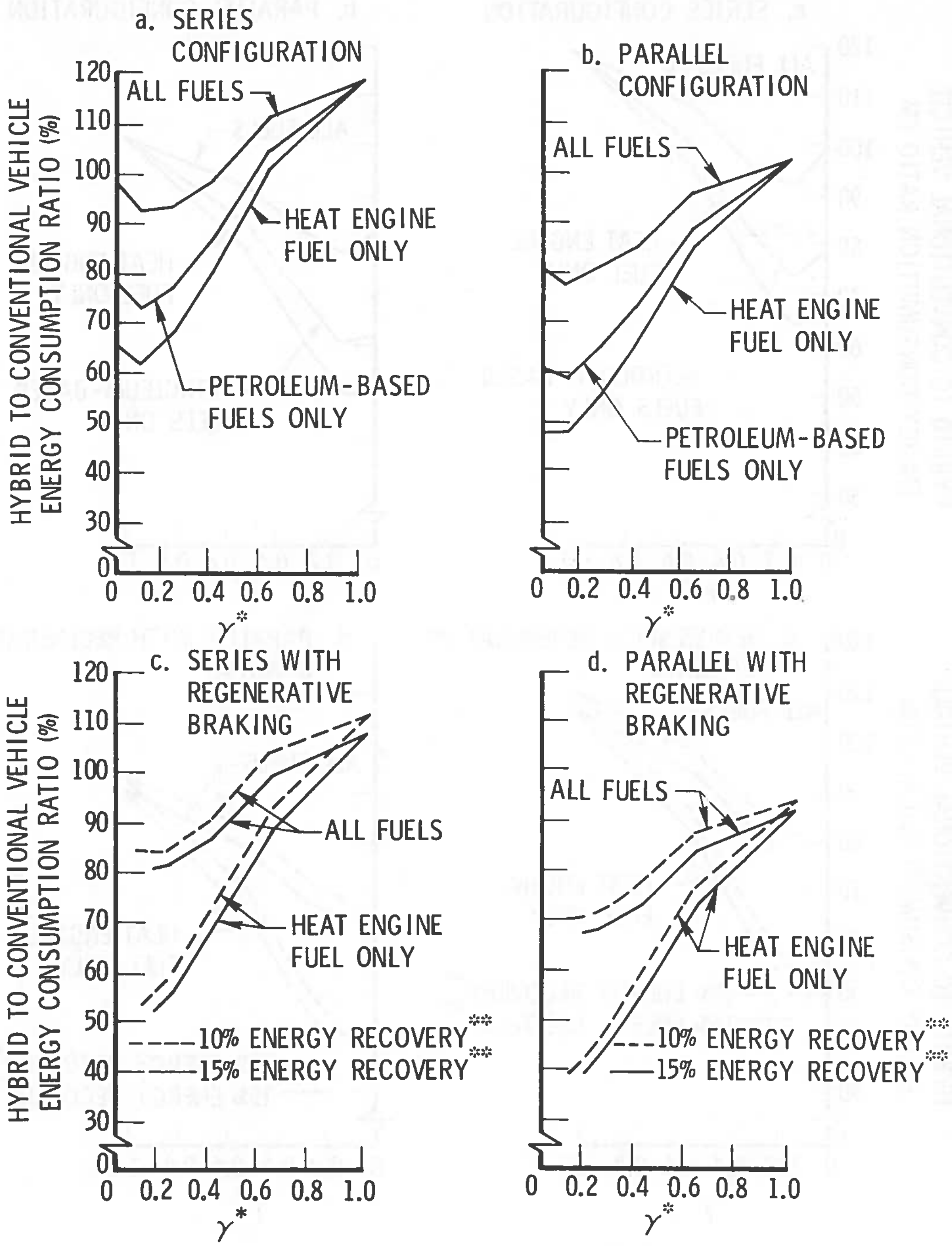
To consume less heat engine fuel (gasoline) than the baseline comparison vehicle, the hybrid vehicle would have to use heat engine fixed



*Fraction of battery recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in battery

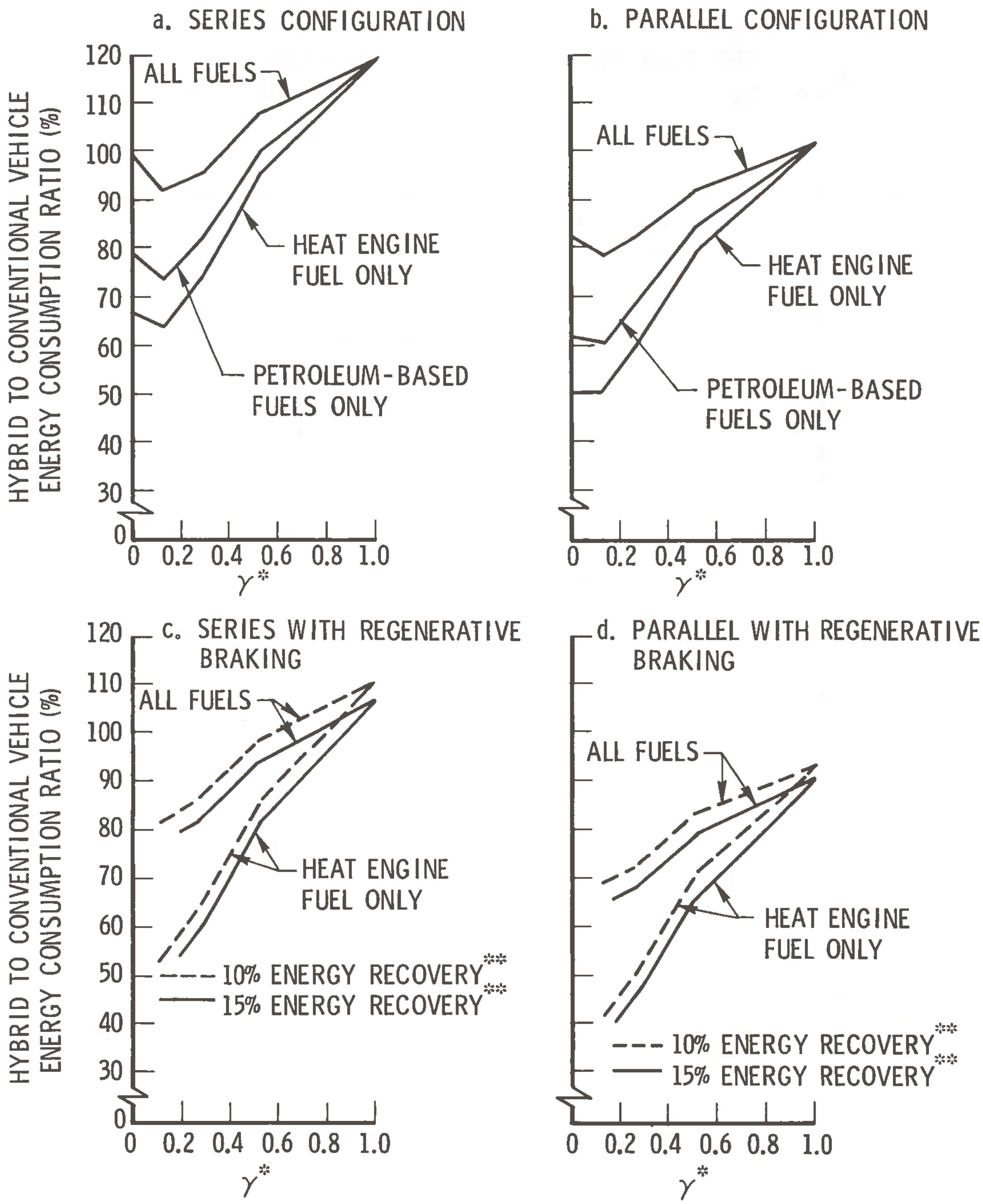
FIGURE S-8. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of battery recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in battery

FIGURE S-9. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of battery recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in battery

FIGURE S-10. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

minimum power settings that provide less than 65 percent of the battery recharge energy required over the driving cycle ($\gamma \leq 0.65$). With regard to petroleum-based fuels (heat engine gasoline plus gas and oil at the electric generating power plant), to use less energy than the baseline vehicle less than 55 percent of the battery recharge energy would be provided by the heat engine ($\gamma \leq 0.55$). Total energy savings (gasoline plus all fuels at the electric generating plant) are achieved when less than 44 percent of the battery recharge energy would be provided by the heat engine.

As the value of γ decreases and the heat engine supplies a decreasing fraction of the vehicle propulsion energy needs, the preceding curves have shown a decrease in hybrid vehicle-related fuel energy consumption. For the "heat engine fuel only" curves, this trend is certainly expected (barring marked changes in engine efficiency). For the "petroleum-based fuels only" and "all fuels" curves, this trend results from the fact that, even under hybrid operating conditions, the onboard heat engine efficiency is less than the combined efficiencies of the electric generating plants and transmission lines. Therefore, for a given amount of energy delivered, the heat engine will consume more fuel energy. Thus, as γ is reduced and more reliance is placed on electric outlet power for battery recharge energy, less total fuel energy is consumed per vehicle mile traveled.

As shown in Figure S-8b the more efficient parallel configuration of the heat engine/battery hybrid vehicle is approximately equivalent to the conventional baseline vehicle in gasoline consumption when the heat engine is used to provide 100 percent of the battery recharge energy ($\gamma = 1.0$). Thus, both gasoline and total energy are conserved in increasing amounts as the fixed minimum power level of the heat engine is reduced and as more electric outlet recharge energy is used (as γ becomes smaller).

Figures S-8c and S-8d illustrate the effect of regenerative braking on energy consumption for the series and parallel configurations, respectively. For the series configuration with 15 percent energy recovery,* operation of the hybrid vehicle at γ values below 0.9 would be required to save

*Percent of total driving cycle energy recovered and stored in battery by regenerative braking system gasoline, and operation below 0.8 would be required to conserve total energy. With 10 percent energy recovery, these γ values become 0.8 and 0.6, respectively. Significant gasoline and total energy savings are accomplished for all γ values with either 10 or 15 percent energy recovery (with increased savings as γ is reduced).

S.4.1.2 2500-lb Car

The energy consumption characteristics of the 2500-lb heat engine/battery hybrid vehicle over the EPA Urban Driving Cycle are illustrated in Figure S-9. Here, the basis of comparison is the gasoline energy consumption of the 2500-lb vehicle of Table S-2 (21.7 mpg or 1.56 kW-hr/mi). The basic effects of configuration (series compared with parallel) and of regenerative braking are similar to those described for the 4000-lb car.

S.4.1.3 6000-lb Van

Figure S-10 depicts the energy consumption characteristics of the 6000-lb hybrid vehicle, as compared with the gasoline energy consumption of the baseline vehicle of Table S-2 (9.3 mpg or 3.64 kW-hr/mi). Again, the basic effects of configuration and of regenerative braking are similar to those described for the 4000-lb and 2500-lb hybrid vehicles.

S.4.1.4 Range Implications

The preceding plots of energy expenditure as a function of γ have shown the potential for hybrid heat engine/battery vehicles to conserve energy, particularly at the lower values of γ. For any value of γ less than 1.0 the onboard heat engine provides only a portion of the battery recharging needs, and the balance of battery recharging must be accomplished by energy from electric generating plants. Whenever the battery is depleted of energy, operation in this manner requires the vehicle to be recharged from an electric outlet for several hours and implies that overnight charging, charging at place of work, or battery exchange are necessary considerations. Hence, the vehicle operating range is affected by the particular γ value used in the design of a hybrid vehicle, and it is of interest to view energy expenditures when plotted as a function of range. The vehicle design range to be discussed is for operation on a given type of driving cycle under standardized conditions with full vehicle power available, but it does not account for variations that might be induced by local climate or terrain encountered in actual driving situations.

Hybrid vehicle design operating range is limited by the more restrictive of two factors: (a) heat engine rate of fuel consumption and fuel tank size, and (b) rate of depletion of stored battery energy and battery size. An example of the range variation with γ for each of the aforementioned considerations is shown in Figure S-11.

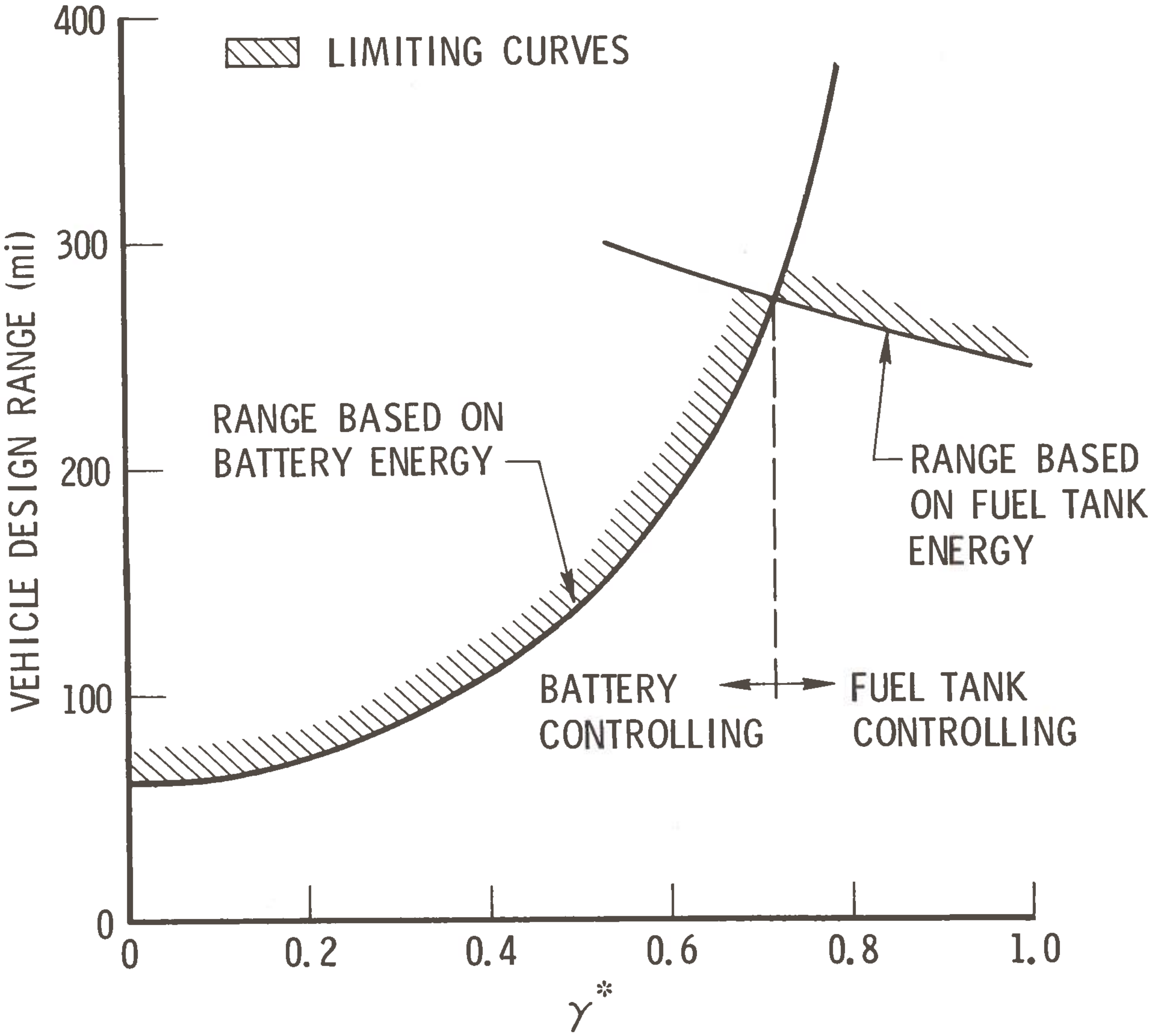
Recall that, as γ increases, the heat engine provides an increasing amount of battery recharge energy. Hence, for a given rate of battery energy expenditure per mile, as γ increases, the vehicle can travel a greater distance before the battery stored energy is finally depleted. This is shown in Figure S-11 by the "range based on battery energy" curve.

Alternatively, though, as γ increases the engine power increases to deliver more recharge energy, and its fuel consumption increases. Therefore, for a given size fuel tank (given amount of stored energy), the vehicle will travel shorter distances. This is shown by the "range based on fuel tank energy" curve.

By selecting the more restrictive case at any γ, it can be seen that, at the higher values of γ, range is based on fuel tank energy, while, at the lower values of γ, range is based on battery energy. Regardless of whether battery or fuel tank is controlling, the full design operating range is determined by calculating the energy expenditure per mile for a given driving cycle and dividing this figure into the stored energy available for propulsion.

In the battery controlling regime, additional range could possibly be extracted after the battery had been exhausted by overriding the vehicle control system and using the heat engine for all propulsion power. Due to the inherent design feature of slow engine response to driver demands, this would result in markedly reduced vehicle acceleration, but, as a backup system, would allow the driver to avoid being stranded.

To construct the curves of energy consumption as a function of range, curves similar to those shown in Figure S-11 were used in conjunction



*Fraction of battery recharge energy supplied by heat engine

FIGURE S-11. HYBRID HEAT ENGINE/BATTERY VEHICLE OPERATIONAL RANGE: 4000-LB CAR, 65-MPH DESIGN CRUISE SPEED, SERIES CONFIGURATION with curves like those shown in Figures S-8 through S-10. Because the range limiting curves give a double value for γ at certain vehicle ranges (in this case between 245 and 275 miles as seen in Figure S-11), a selection criterion was necessary. It was provided by observing that energy consumption always showed an increase with γ. Therefore, the lower γ value was selected to have the system operate at the lesser of the two possible values for energy consumption. This means that for the vehicle energy consumption curves presented, the battery is always range-controlling.

S.4.1.5 Impact of Design Peak Cruise Speed, Design Peak Acceleration, Vehicle Weight, and Regenerative Braking

For a 4000-lb series configuration car designed for different peak cruise speeds, energy consumption relative to the baseline, conventionally powered, car is shown in Figure S-12 as a function of vehicle design range. Curves for consumption of all fuels and for consumption of only petroleum-based fuels are depicted. An example of the double-valued solution for energy consumption mentioned previously is shown for the 65-mph cruise case.

The results indicate that total energy savings are possible for vehicles designed for reduced cruise speeds of 55 and 65 mph and having daily operating ranges less than about 105 and 115 miles, respectively. When considering saving only petroleum-based fuels for these reduced-speed vehicles, comparable range values are 200 and 155 miles, respectively. At the lowest range shown, these hybrid vehicles consume about 85 to 90 percent of the energy of conventionally powered vehicles and about 65 to 70 percent of the petroleum-based fuel. These hybrid vehicles also have maximum possible design operating ranges slightly less than conventionally powered vehicles.

The high-speed, 80-mph cruise vehicle shows virtually no savings in total energy, but petroleum-based fuel consumption can be reduced if design operating range is limited to less than 95 miles. The maximum possible range is significantly less than that of the conventionally powered car.

While the vehicle design peak cruise speed does show a significant effect on energy consumption, this is not evident for the vehicle design

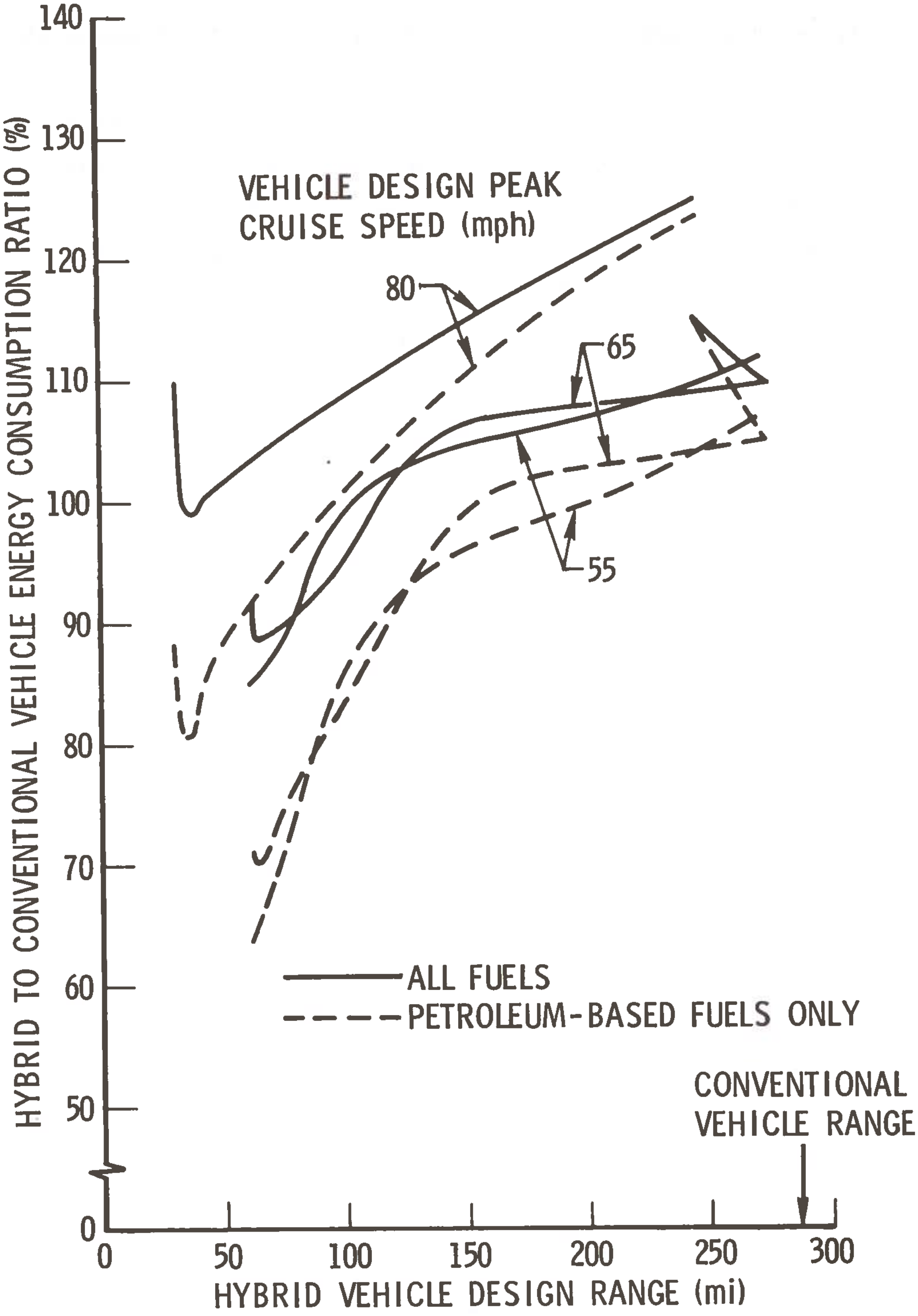


FIGURE S-12. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE WEIGHT = 4000 LB, SERIES CONFIGURATION peak acceleration. Generally, only minor differences would come about due to slight changes in motor efficiency as the size varies to meet the wheel power requirements during a sustained acceleration run. Changes in gear ratio to meet wheel torque requirements would cause the motor to operate at different speeds, and this would also introduce some small changes in efficiency. The major impact on vehicle operation is to be found in the battery design requirement area. As design acceleration increases and power delivery needs increase, powertrain component weights must increase accordingly. The weight available for batteries then decreases, and the required battery specific power (W/lb) rises sharply. The reduction in available battery weight would likewise reduce the available ampere-hour capacity. This would have two effects: (a) the vehicle minimum operational range would be decreased, and (b) allowable battery charging rates would be reduced, with the potential for wasting more energy during battery recharge.

To illustrate the effect of vehicle weight, a set of energy consumption curves is shown in Figure S-13 for a constant design peak cruise speed of 65 mph for three different series configuration vehicle weights: 2500, 4000, and 6000 lb. The lowest energy consumption and greatest possible design operating range is found with the 4000-lb car which, as had been shown in Figure S-12, has energy savings at design operating ranges less than 115 miles for all fuels and less than 155 miles for petroleum-based fuels. The poorest results are shown by the 2500-lb car, which results in fuel savings only below the 75-mile range for all fuels and below 110 miles for petroleum-based fuels. Intermediate results are shown for the 6000-lb van with commensurate range values of 100 and 140 miles.

A uniform trend of relative energy consumption with vehicle weight is not evident from Figure S-13. This is because, in lieu of other available data, results for the 6000-lb van have had to be compared to the energy consumption of a conventionally powered 6000-lb car, rather than a conventionally powered 6000-lb van. The higher aerodynamic drag profile of the van causes significantly greater expenditure of energy than a car, even at the moderate speeds of the urban cycle. If a 6000-lb hybrid automobile had been analyzed, then the curves in Figure S-13 would have shown a definite trend of decreasing relative energy consumption with increasing vehicle weight.

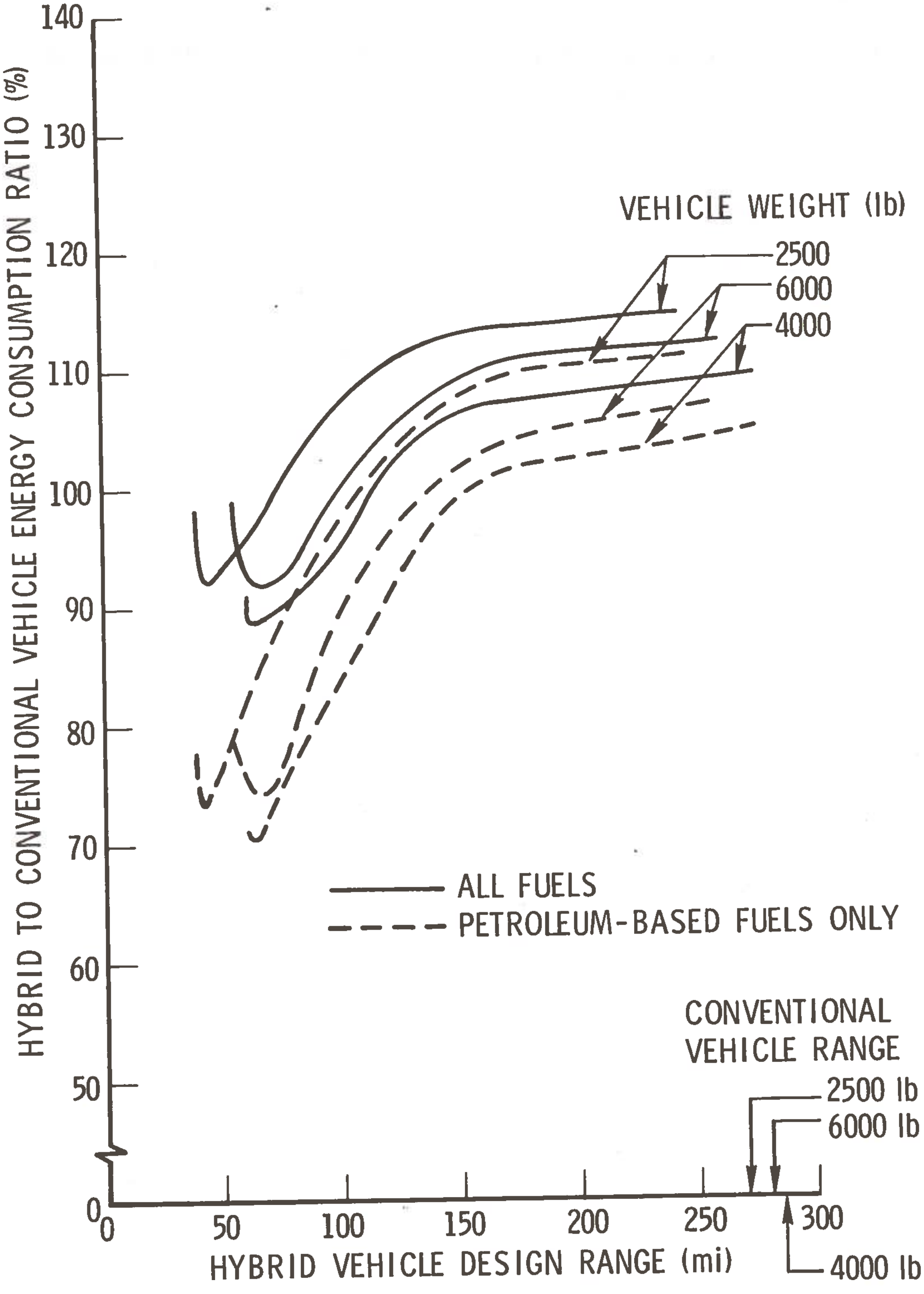


FIGURE S-13. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION

Curves for the same vehicle weights were constructed to illustrate, as a function of vehicle design operating range, the effect of regenerative braking on energy consumption for both series and parallel configurations, when compared with the baseline, conventionally powered vehicle. The impact of regenerative braking is quite dramatic, as seen in Figures S-14 through S-16 for the series configuration. With 15 percent of vehicle drive wheel energy recovered in the battery, energy savings are possible at all ranges shown for the 4000-lb hybrid car and the 6000-lb hybrid van. If only petroleum-based fuels are considered, a 10 percent recovery of energy is sufficient to produce a similar result. The 2500-lb car continues to show relatively higher energy expenditures than the other hybrid vehicles. Energy savings are possible throughout the vehicle design operating range only for 15 percent energy recovery and a petroleum-based fuel reference criterion. At reduced design operating range, the energy savings are quite impressive for all vehicles; almost 30 percent savings in petroleum-based fuels are shown at the 100-mile range for the 4000-lb car with 15 percent energy recovery.

Still greater energy savings are possible with the parallel configuration, as seen in Figures S-17 through S-19. Even without regenerative braking, energy savings are available for all vehicles over the entire design operating range. Both the 4000-lb car and the 6000-lb van have equivalent savings over the conventionally powered vehicle. At the 300-mile range and with 15 percent recovery of vehicle drive wheel energy, the 4000-lb car shows savings of better than 15 percent for all fuels and better than 20 percent for petroleum-based fuels. At a reduced design operating range of about 100 miles, these figures change to 25 and 35 percent, respectively.

If, as stated earlier, engine BSFC can be held to the same values as those associated with the series configuration, the parallel configuration is preferred over the series configuration for the driving that is characterized by the EPA Urban Driving Cycle. Regenerative braking also provides significant energy conservation. If the added system complexity and cost can be justified, every effort should be made to include a prototype regenerative braking system in any future hybrid vehicle to verify the energy recovery

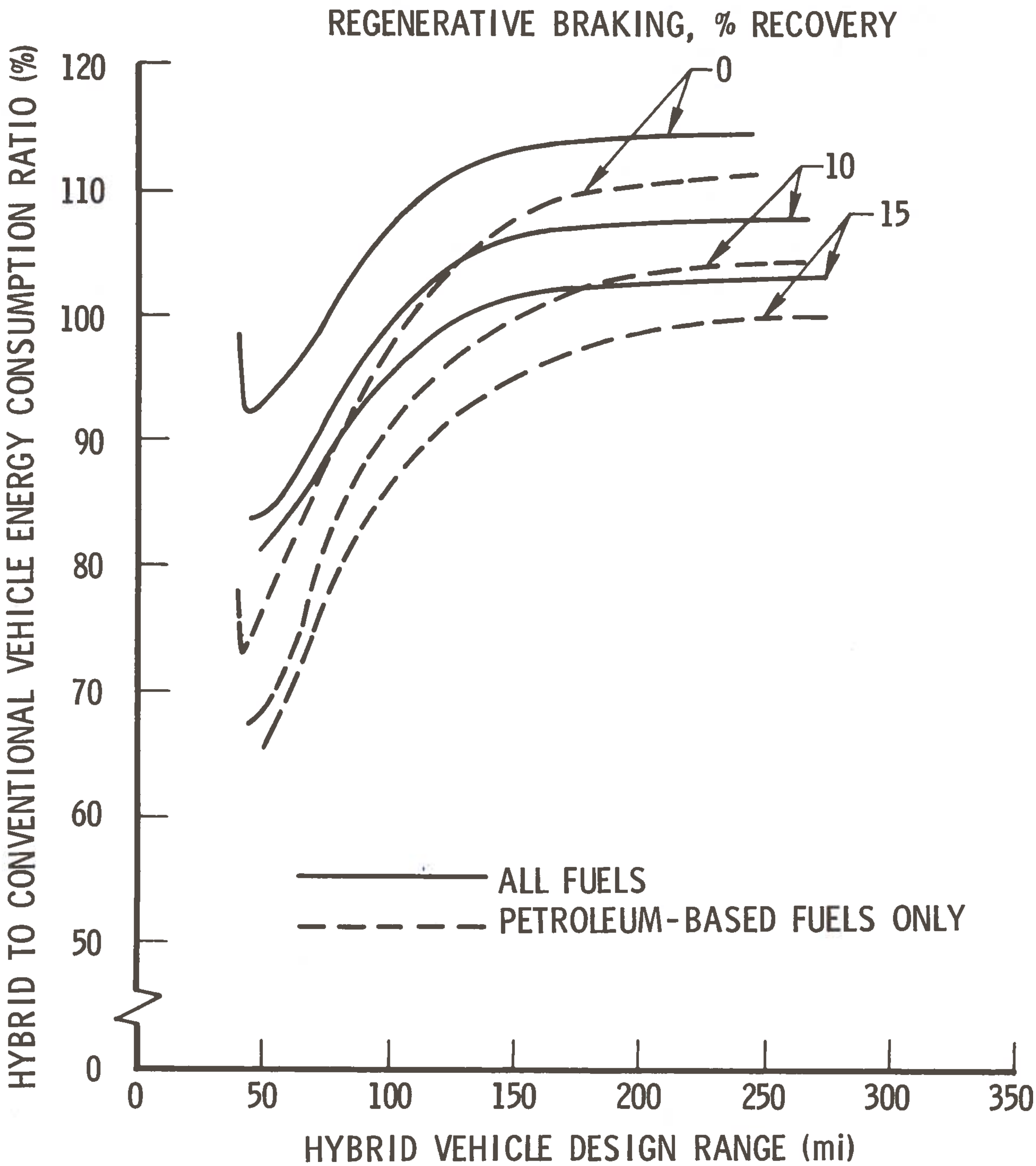


FIGURE S-14. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, SERIES CONFIGURATION

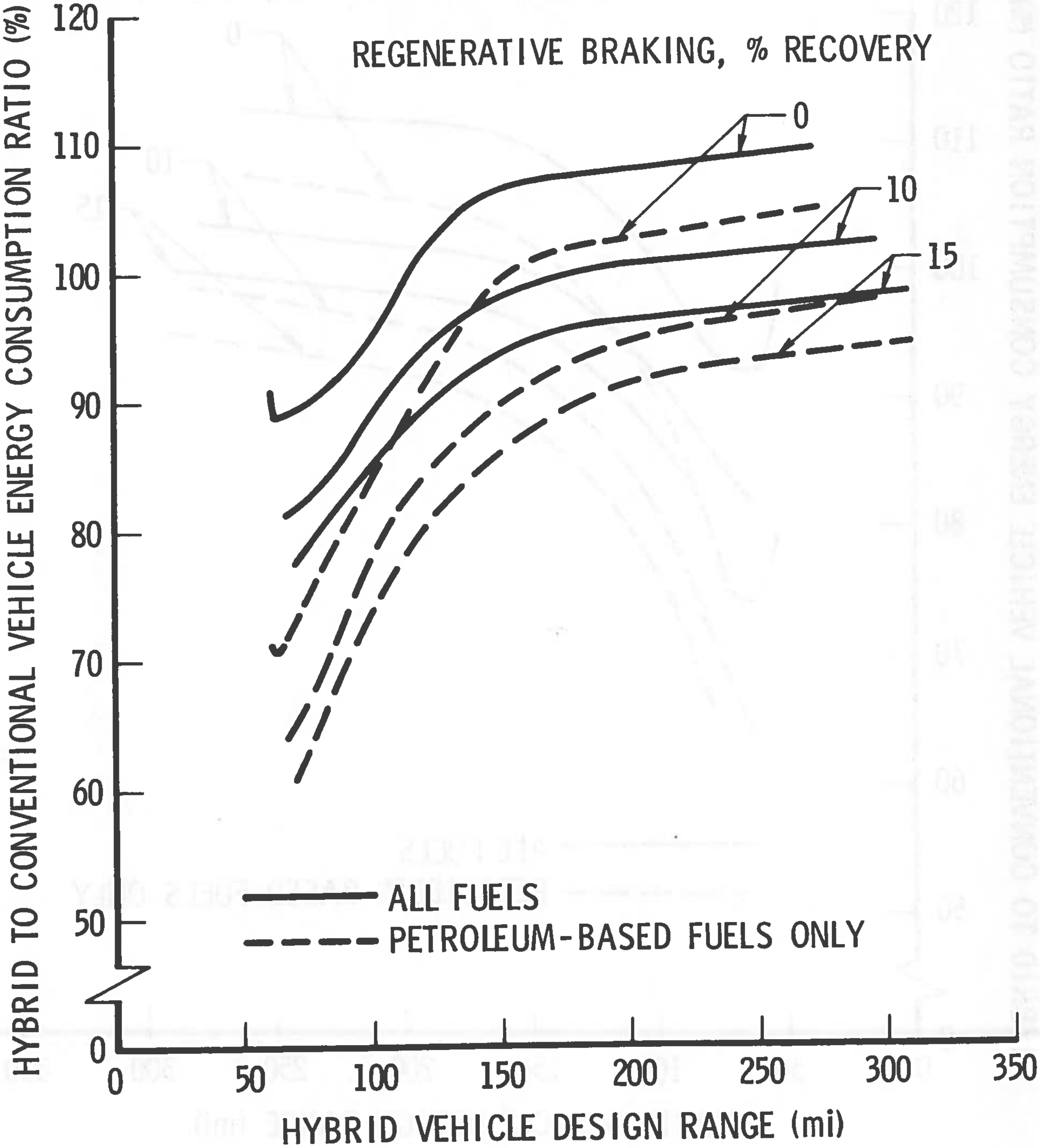


FIGURE S-15. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, SERIES CONFIGURATION

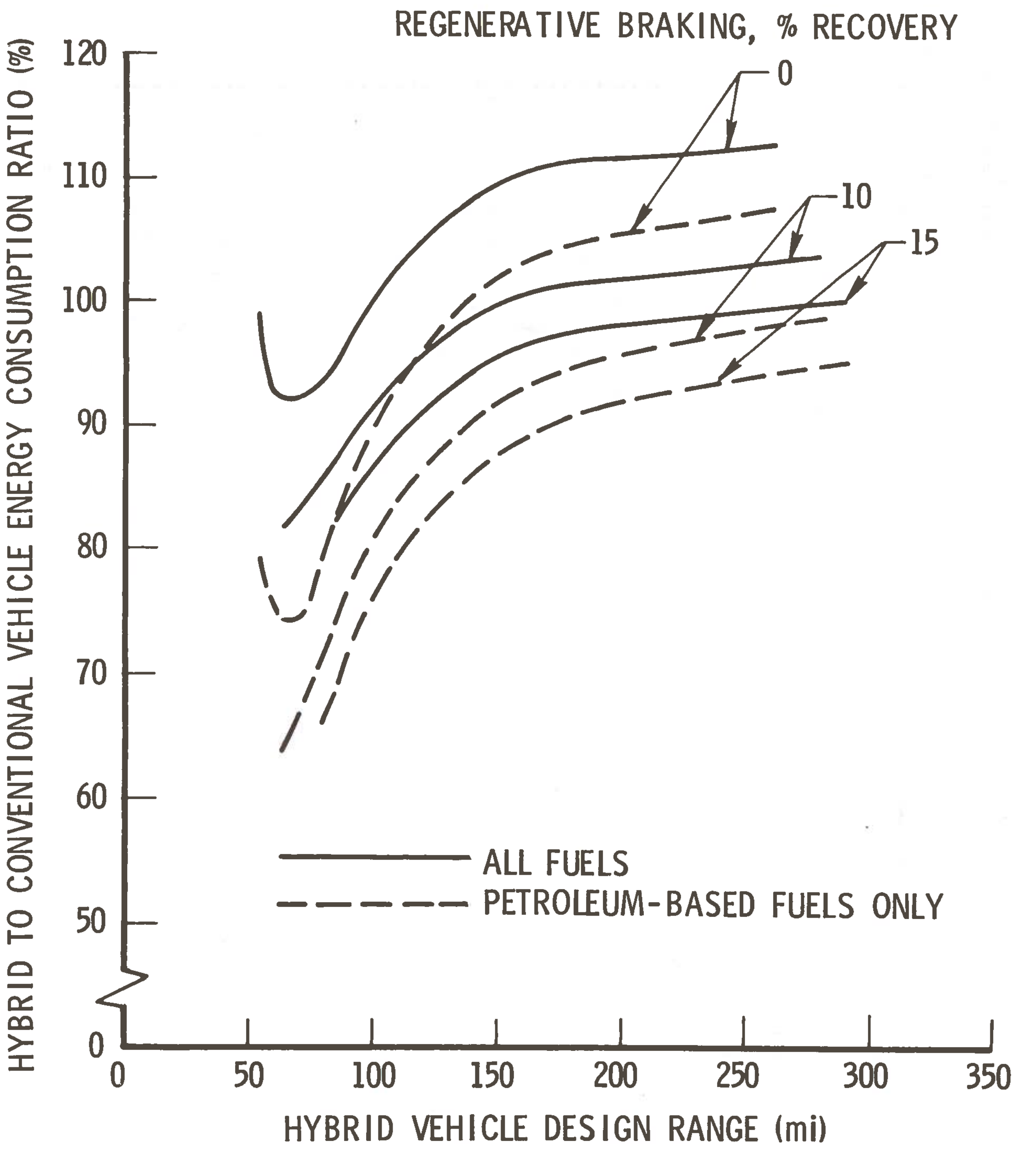


FIGURE S-16. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, SERIES CONFIGURATION

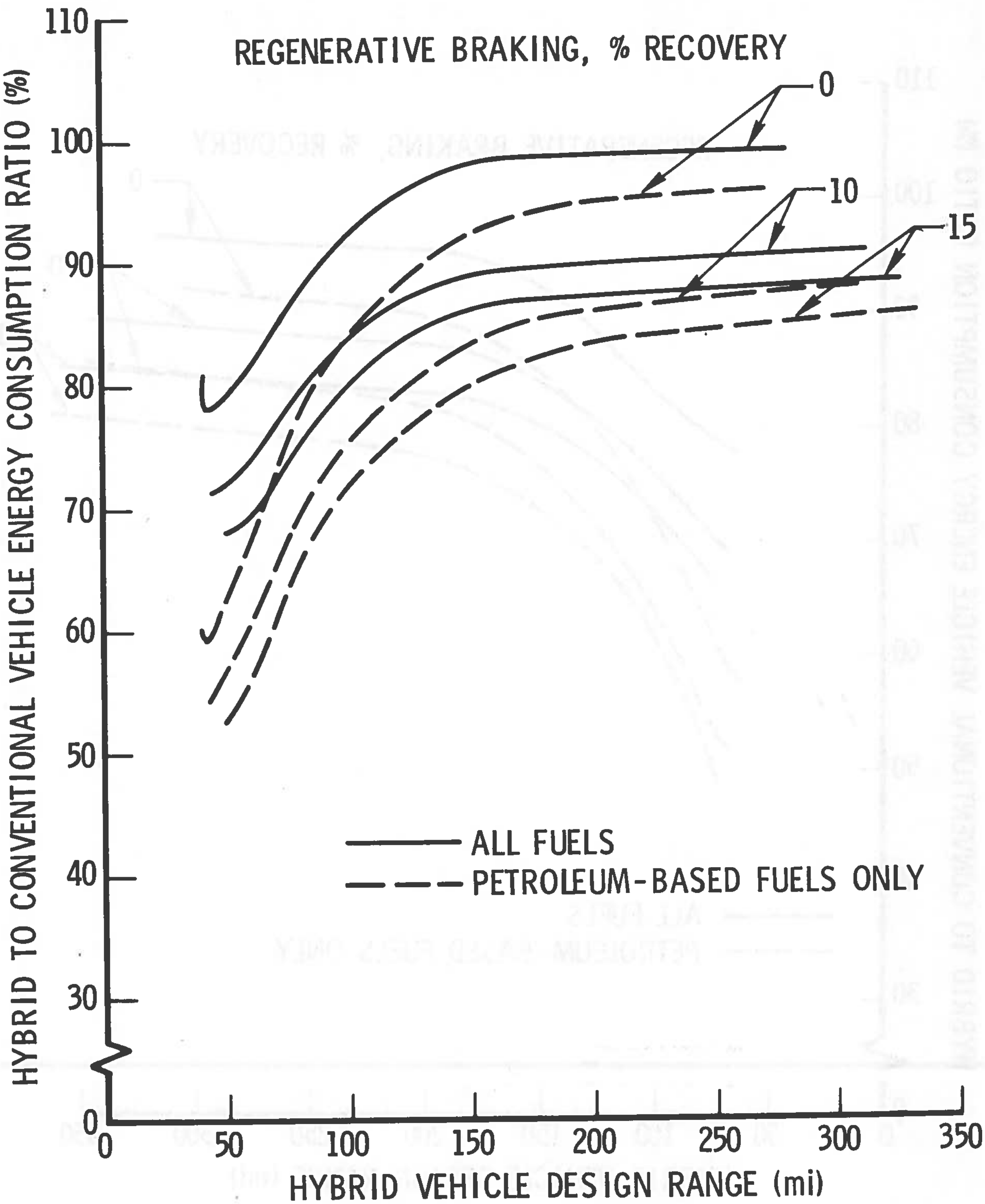


FIGURE S-17. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, PARALLEL CONFIGURATION

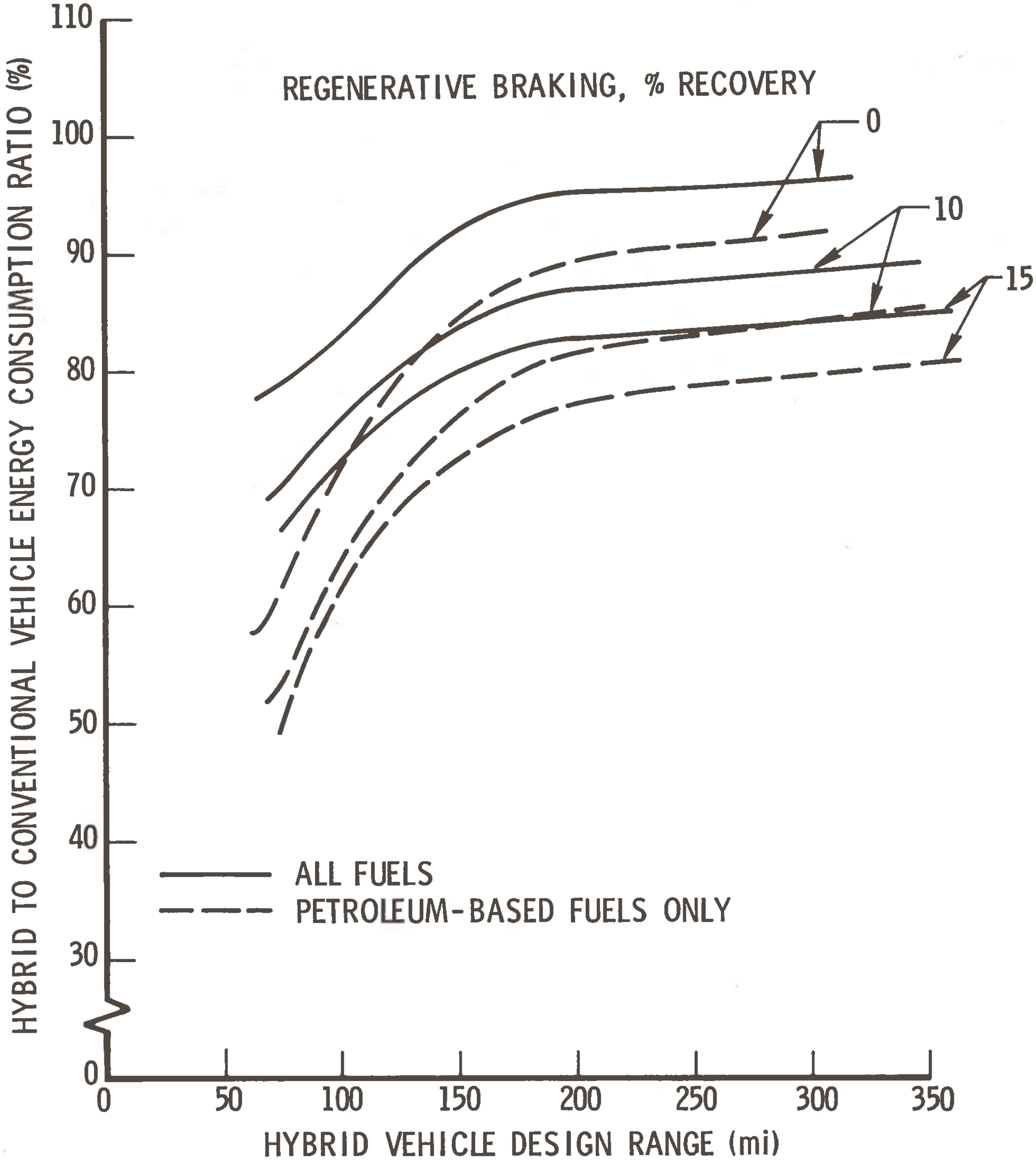


FIGURE S-18. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, PARALLEL CONFIGURATION

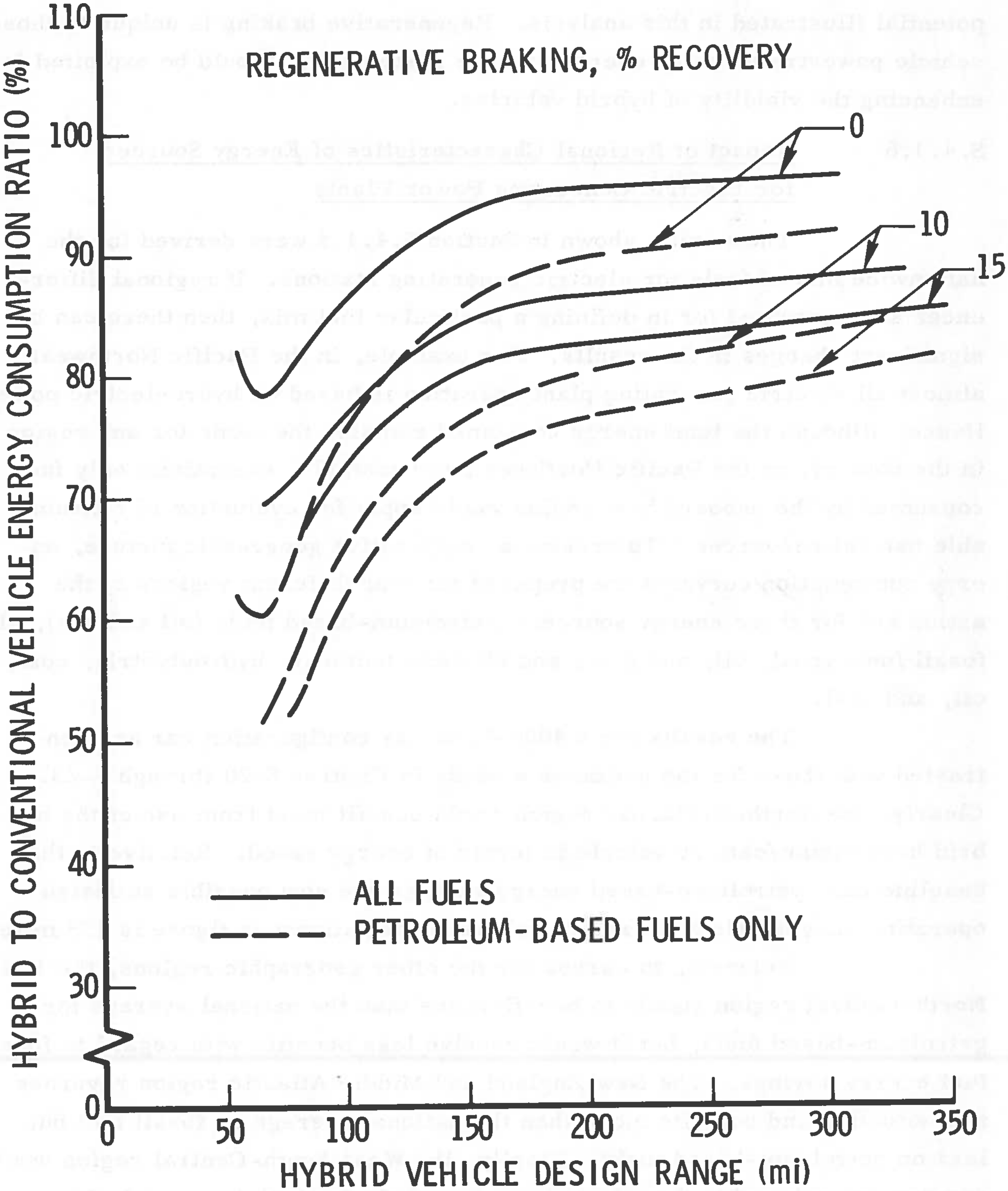


FIGURE S-19. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, PARALLEL CONFIGURATION potential illustrated in this analysis. Regenerative braking is unique to those vehicle powertrains using energy storage systems and should be exploited for enhancing the viability of hybrid vehicles.

S.4.1.6 Impact of Regional Characteristics of Energy Sources for Electric Generating Power Plants

The results shown in Section S.4.1.5 were derived for the nationwide mix of fuels for electric generating stations. If regional differences are accounted for in defining a particular fuel mix, then there can be significant changes in the results. For example, in the Pacific Northwest almost all electric generating plant operation is based on hydroelectric power. Hence, although the total energy consumed remains the same for any region in the country, in the Pacific Northwest, for example, essentially only fuel consumed by the onboard heat engine would apply for evaluation of consumable natural resources. To present a comparative geographic picture, energy consumption curves were prepared for four different regions of the nation and for three energy sources: petroleum-based fuels (oil and gas), all fossil fuels (coal, oil, and gas), and all fuels (nuclear, hydroelectric, coal, oil, and gas).

The results for a 4000-lb series configuration car are contrasted with those for the nation as a whole in Figures S-20 through S-23. Clearly, the Northern Pacific region would benefit most from use of the hybrid heat engine/battery vehicle in terms of energy saved. Relative to the baseline car, petroleum-based energy savings are now possible at design operating ranges below 220 miles, whereas the nationwide figure is 155 miles.

Referring to curves for the other geographic regions, the East-North-Central region stands to benefit more than the national average for petroleum-based fuels, but it would receive less benefits with regard to fossil fuel energy savings. The New England and Middle Atlantic region reverses this situation and benefits more than the national average on fossil fuel but less on petroleum-based fuels. Finally, the West-South-Central region would receive fewer benefits than the nation as a whole for both types of fuel sources. These conclusions are also equally true for the parallel configuration.

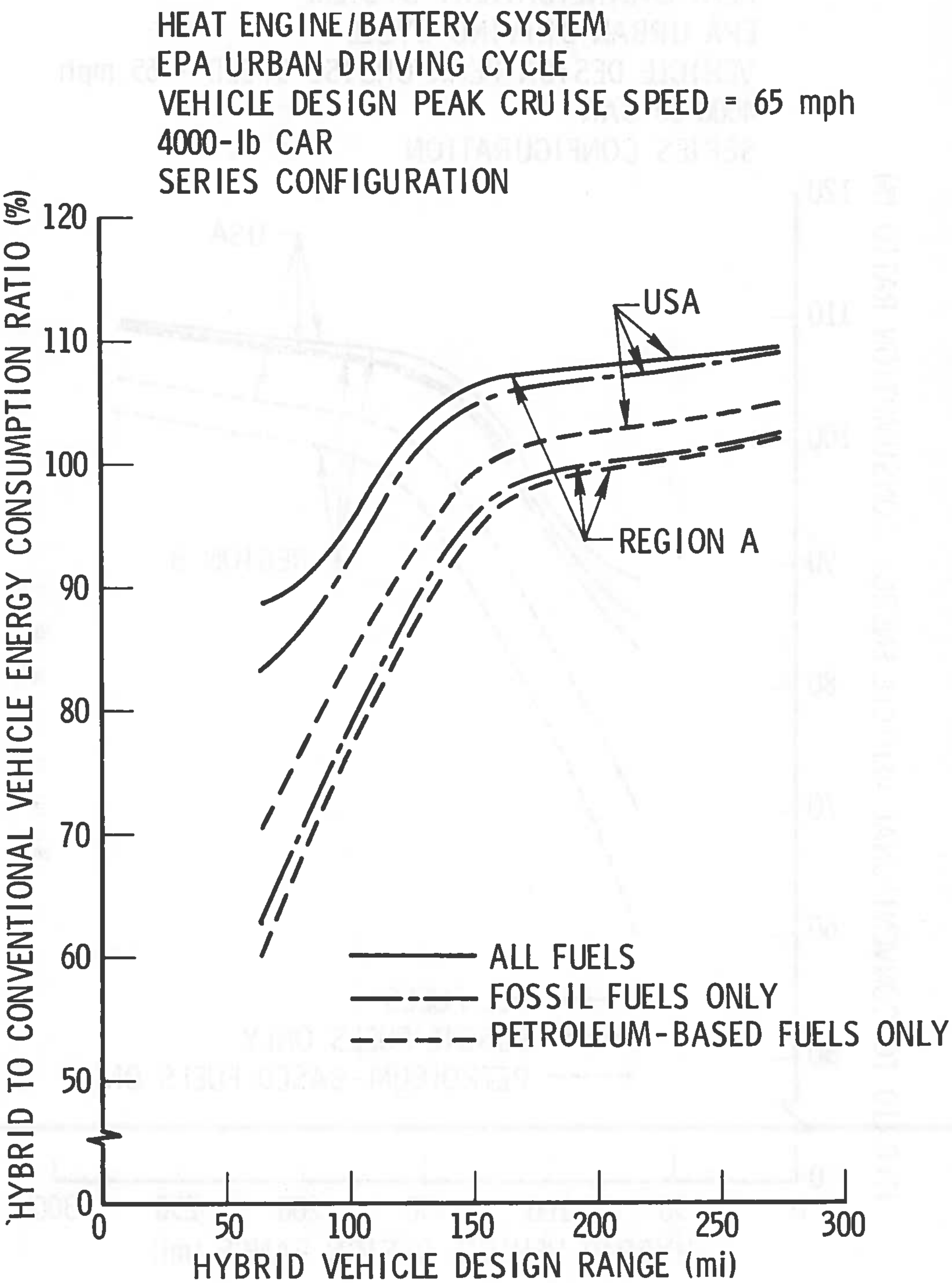


FIGURE S-20. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION A, NORTHERN PACIFIC STATES

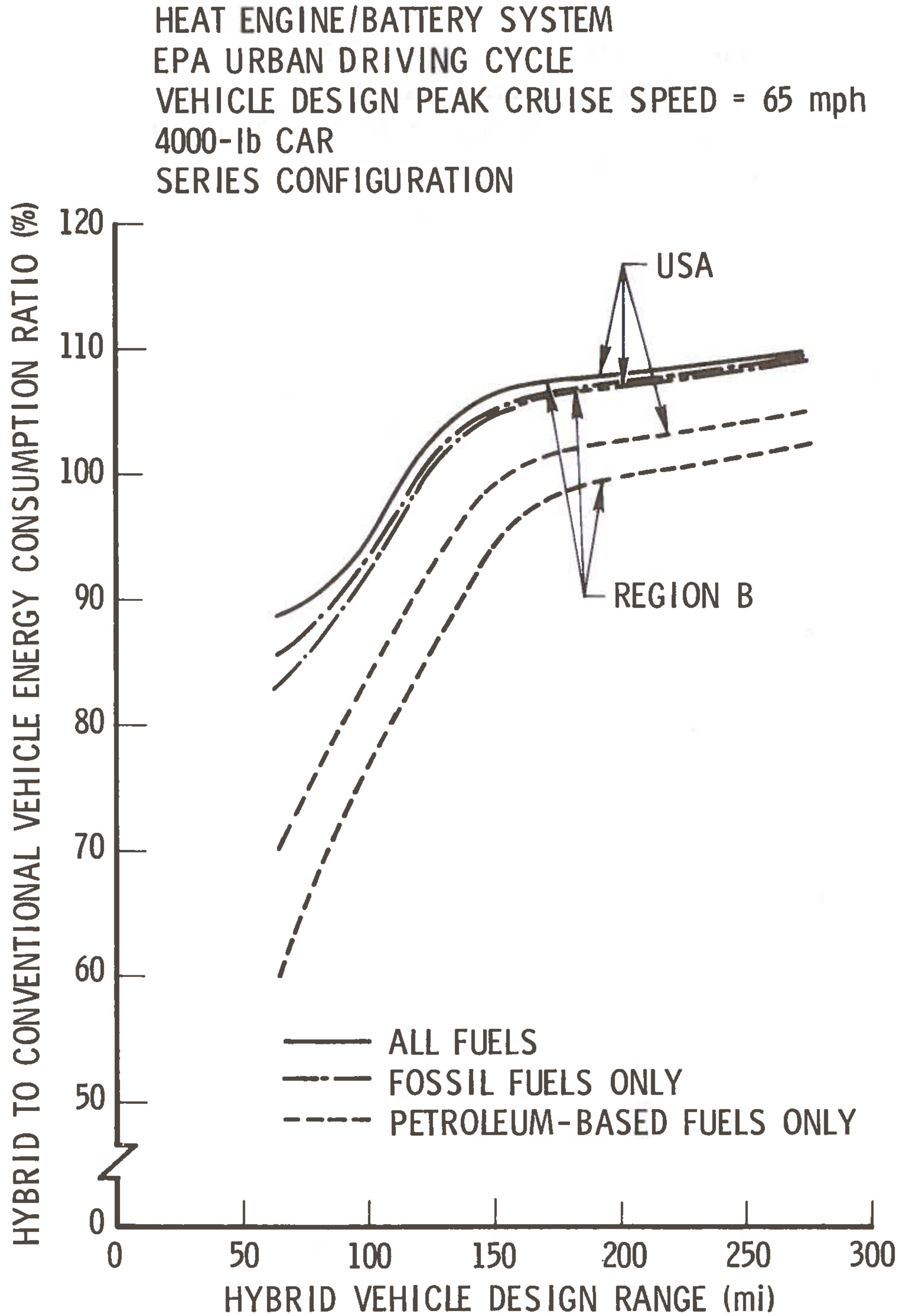


FIGURE S-21. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION B, EAST-NORTH-CENTRAL STATES

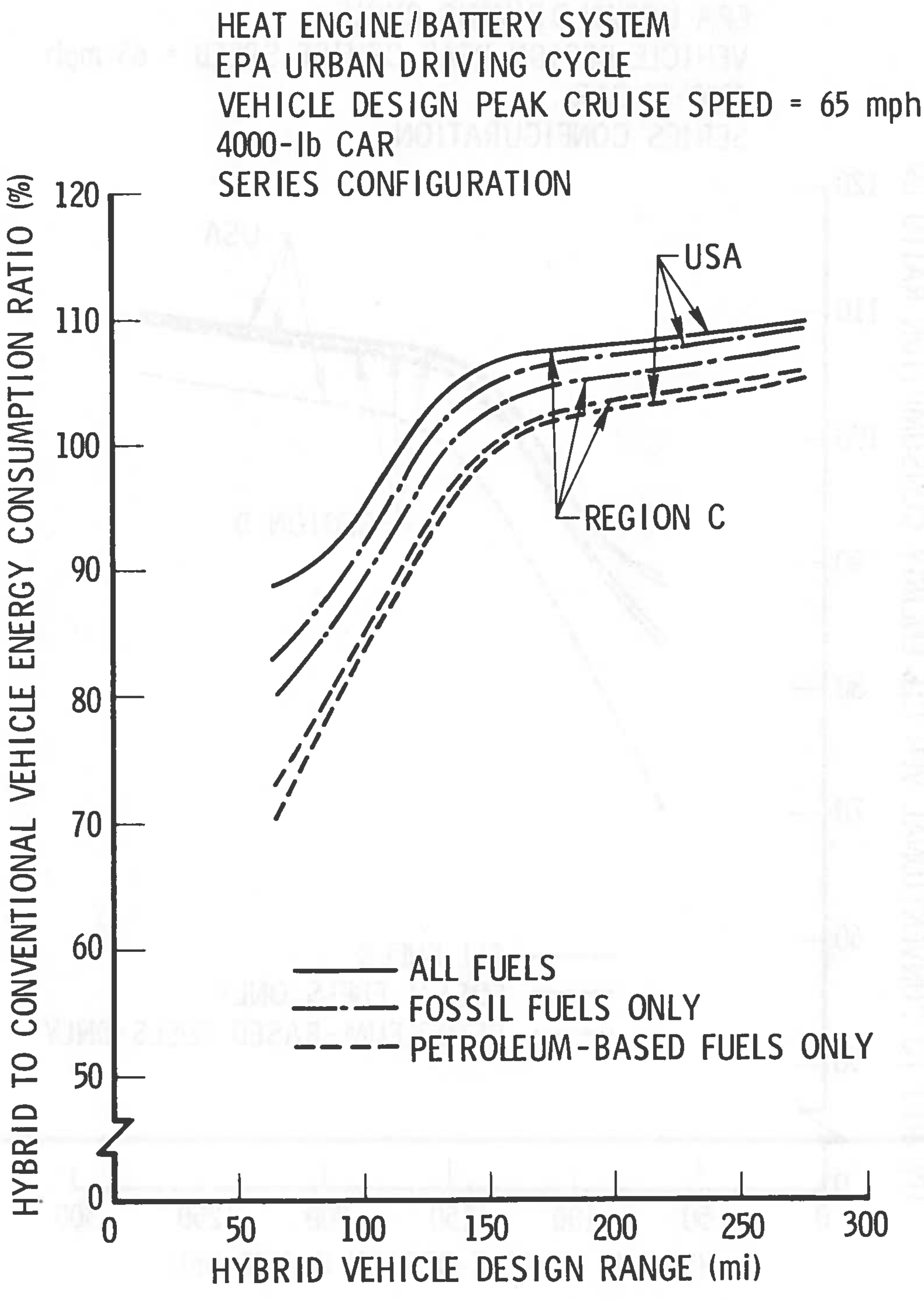


FIGURE S-22. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION C, NEW ENGLAND AND MIDDLE ATLANTIC STATES

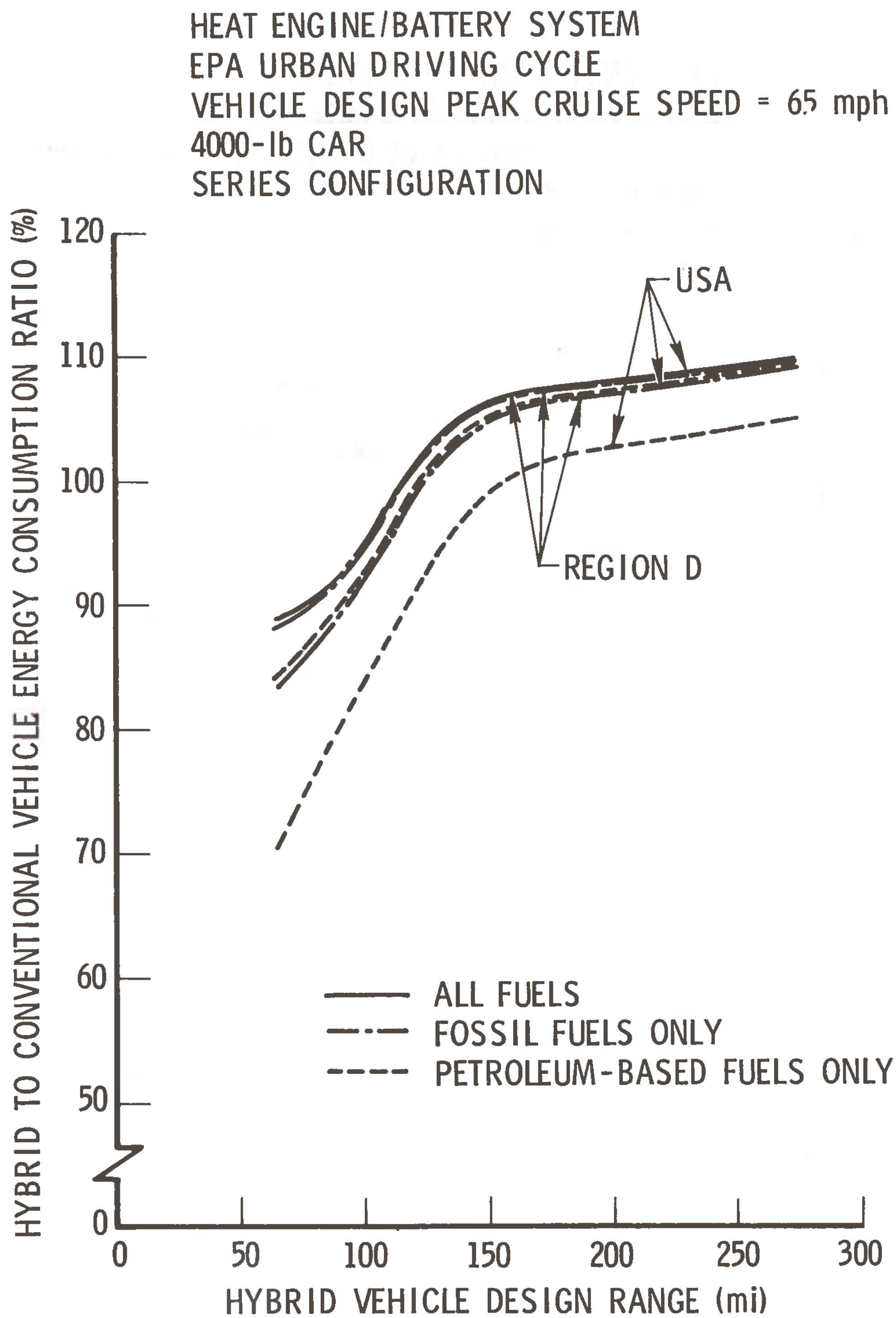


FIGURE S-23. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION D, WEST-SOUTH-CENTRAL STATES

S.4.1.7 Lead-Acid Compared with Nickel-Zinc Batteries

The entire previous discussion was based on results obtained for vehicles relying on nickel-zinc batteries for the energy storage system. If hybrid vehicles were to be designed and implemented prior to availability of nickel-zinc batteries, then lead-acid battery systems would have to be used. To ascertain the energy savings that might be expected, a brief analysis of a 4000-lb series configuration car was included in the study. (The lead-acid battery system analyzed has a specific energy of 12.7 W-hr/lb.)

The results are shown in Figure S-24 where relative energy consumption is plotted as a function of vehicle design operating range. Comparing these results to those previously presented for nickel-zinc shows significant increases in energy consumption at equivalent vehicle range, except at the very low range values. Energy savings would then be possible only at design operating ranges less than 90 miles for all fuels and less than about 130 miles for petroleum-based fuels. Similar effects could be expected for the parallel configuration.

S.4.2 ENERGY CONSUMPTION CHARACTERISTICS FOR THE EPA HIGHWAY DRIVING CYCLE

S.4.2.1 4000-lb Car

The fuel energy consumption characteristics of the 4000-lb heat engine/battery hybrid vehicle operated over the EPA Highway Driving Cycle are illustrated in Figure S-25. The energy consumption of the hybrid vehicle is referenced to the gasoline energy consumption of the conventional baseline 4000-lb vehicle of Table S-2 over the same cycle (at 19.4 mpg or 1.74 kW-hr/mi).

The series configuration (Figure S-25a) consumes approximately 65 percent more energy (and tanked gasoline) than the reference vehicle if the heat engine is used to provide 100 percent of the battery recharge energy. This excessive energy consumption occurs for several reasons. First, the hybrid vehicle is being compared to a conventional vehicle with an engine/transmission combination operating at high efficiency over this driving cycle (the generator and drive motor of the hybrid series configuration have average efficiencies of only 80 and 82 percent, respectively).

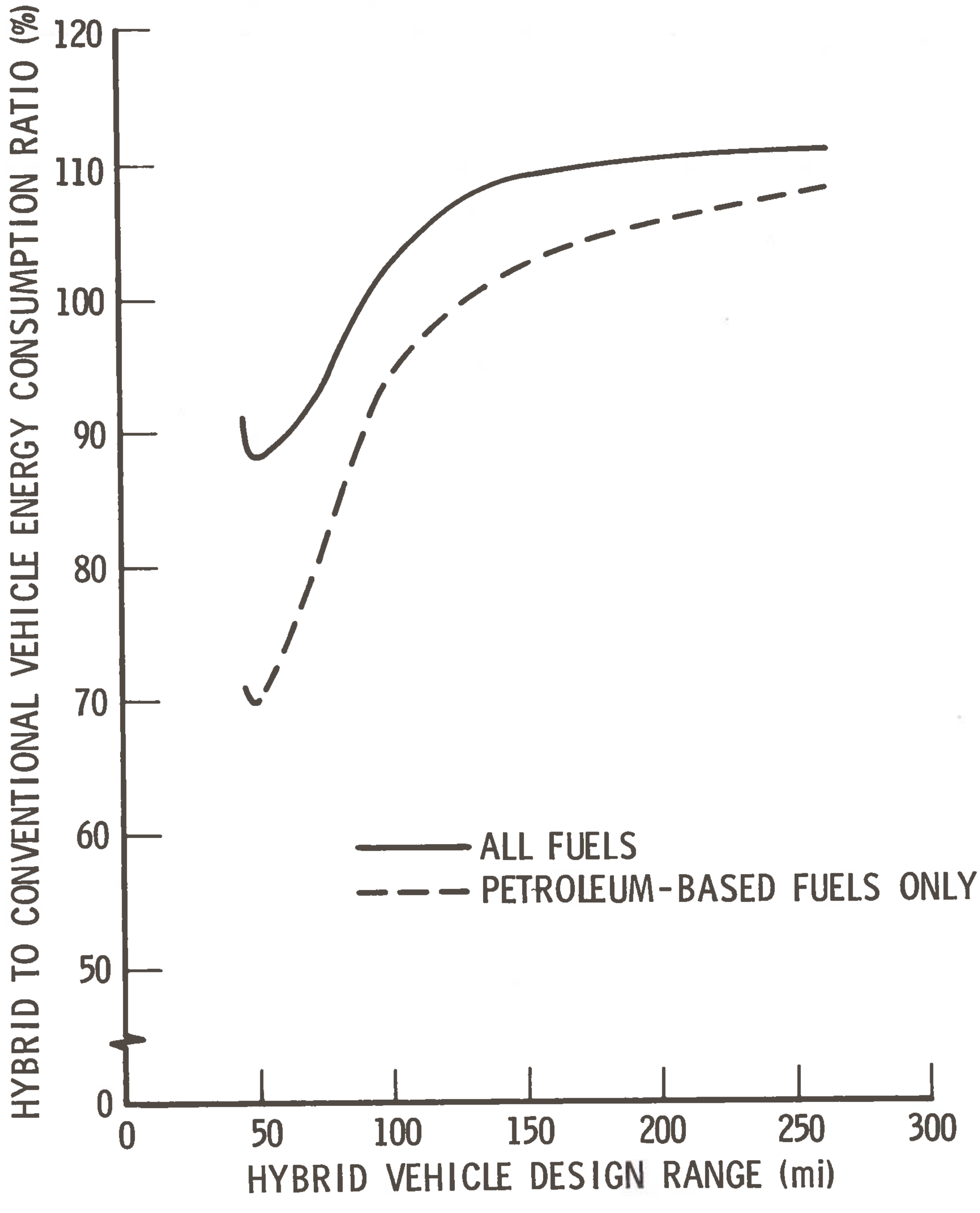


FIGURE S-24. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, LEAD-ACID BATTERY SYSTEM, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, SERIES CONFIGURATION

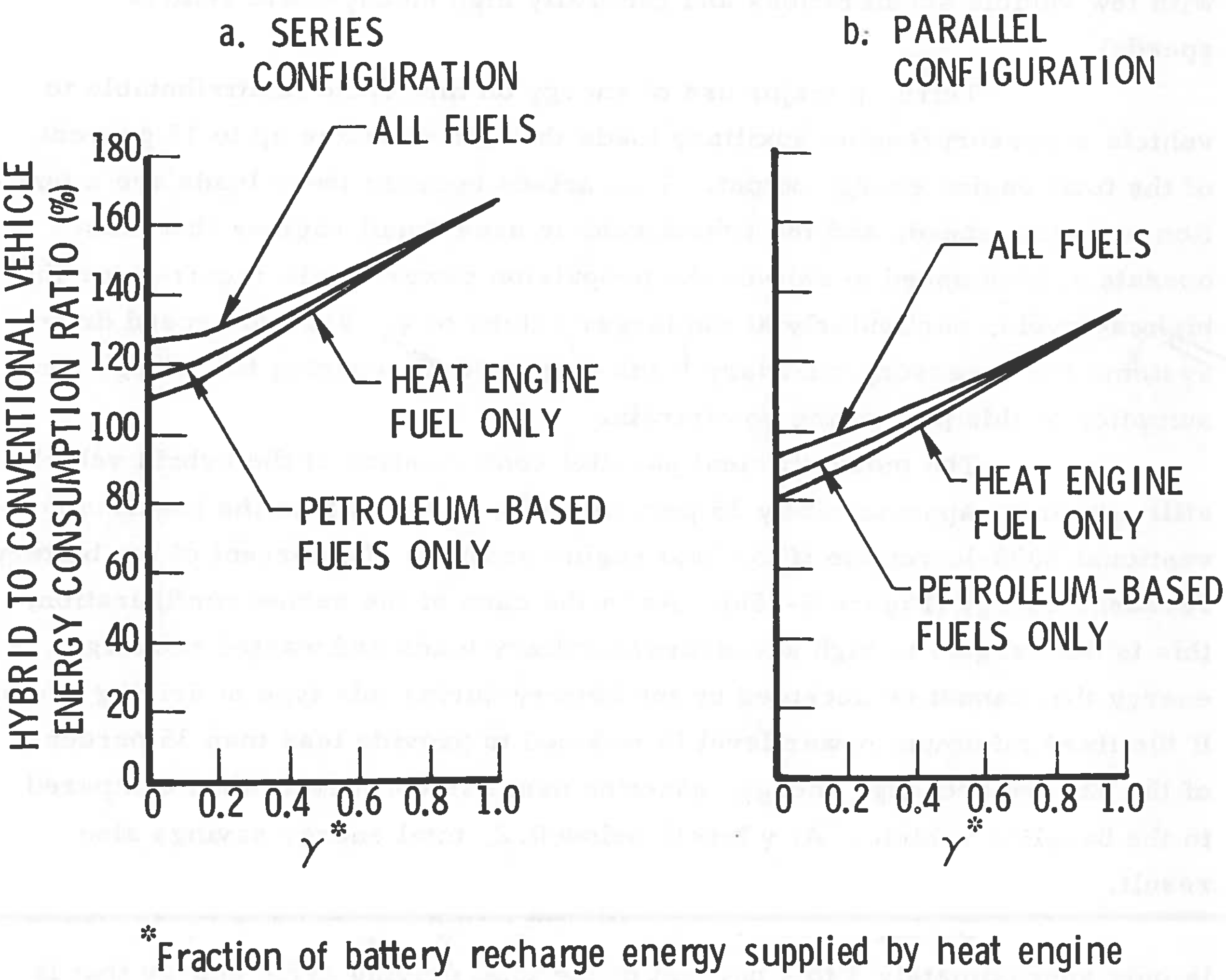


FIGURE S-25. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

Second, the selected analysis requirements are such that (a) the heat engine minimum power level must be maintained throughout the driving cycle and (b) the battery must be fully recharged at the end of the driving cycle. The fixed minimum power level of the heat engine needed to meet this requirement results in the generation of a large amount of battery charging energy that is largely wasted because even without recharging, the battery remains at a high state of charge over this type of driving cycle (i.e., one, with few vehicle accelerations and generally high steady-state vehicle speeds).

Third, a major use of energy on this cycle is attributable to vehicle accessory/engine auxiliary loads that can consume up to 15 percent of the total engine energy output. This arises because these loads are a function of engine speed, and the hybrid vehicle uses small engines that must operate at high speed to deliver the propulsion power levels required for the highway cycle, particularly at the larger values of γ. Variable speed drive systems for accessory/auxiliary loads might aid in reducing the energy consumption of this part of the powertrain.

The more efficient parallel configuration of the hybrid vehicle still consumes approximately 35 percent more gasoline than the baseline conventional 4000-lb vehicle if the heat engine provides 100 percent of the battery recharge energy (Figure S-25b). As in the case of the series configuration, this is due largely to high accessory/auxiliary loads and wasted recharge energy that cannot be accepted by the battery during this type of driving cycle. If the fixed minimum power level is reduced to provide less than 35 percent of the battery recharge energy, gasoline usage is conserved when compared to the baseline vehicle. At γ levels below 0.2, total energy savings also result.

During operation over the EPA Highway Driving Cycle, there is only approximately 3 to 4 percent of the total driving cycle energy that is available for recovery through regenerative braking. This results because of the preponderance of high vehicle speeds combined with a minimal number of vehicle decelerations. Therefore, the effect of regenerative braking on energy consumption is negligible for either the series or parallel configuration.

S.4.2.2 2500-lb Car

The energy consumption characteristics of the 2500-lb heat engine/battery hybrid vehicle over the EPA Highway Driving Cycle are illustrated in Figure S-26. Here, the basis of comparison is the gasoline energy consumption of the 2500-lb vehicle of Table S-2 (31.0 mpg or 1.09 kW-hr/mi). The basic effects of configuration (series compared with parallel) and of regenerative braking are similar to those described for the 4000-lb car.

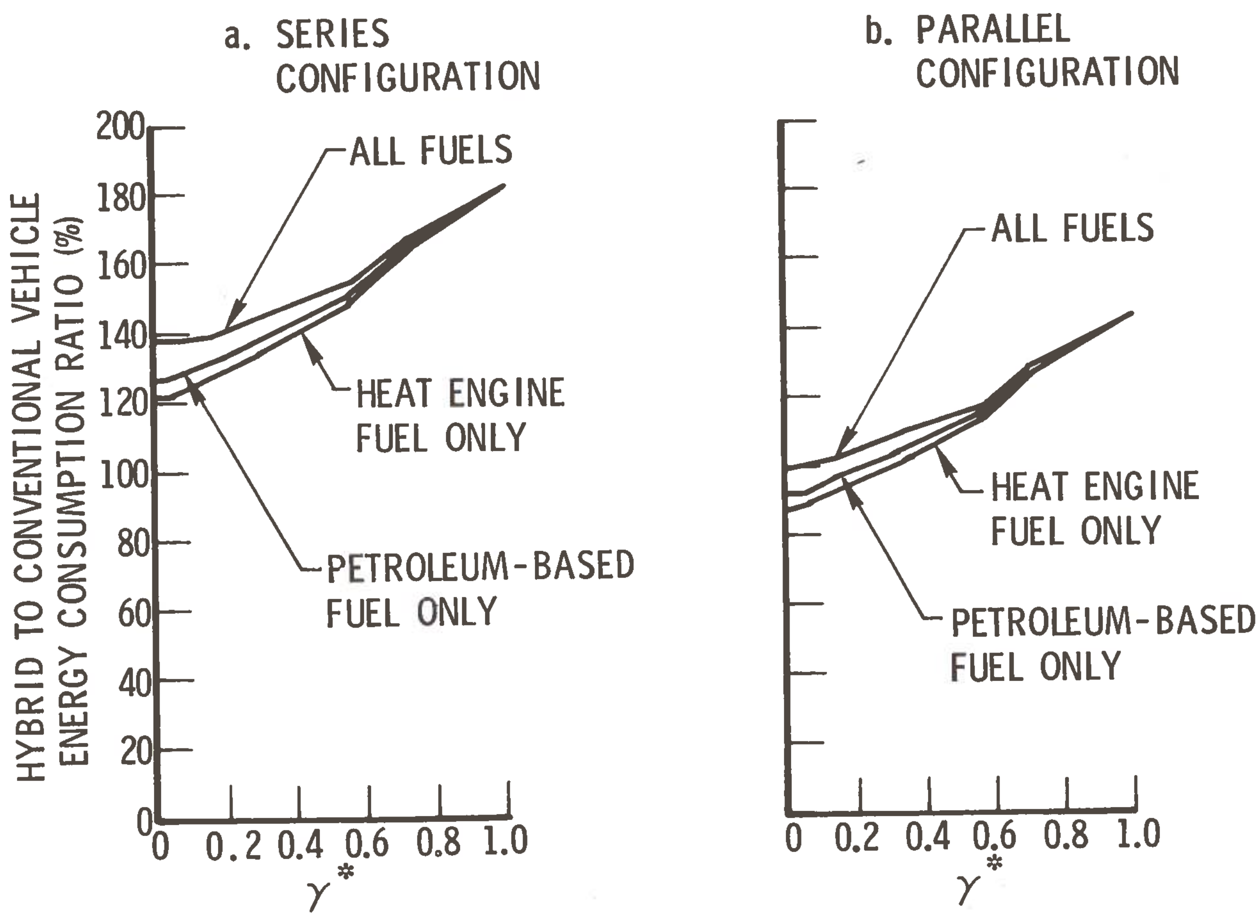
S.4.2.3 6000-lb Van

Figure S-27 depicts the energy consumption characteristics of the 6000-lb hybrid van, as compared with the gasoline energy consumption of the baseline vehicle of Table S-2 (14.1 mpg or 2.4 kW-hr/mi). Again, the basic effects of configuration and of regenerative braking are similar to those described above for the 4000-lb and 2500-lb vehicle. In the case of the 6000-lb van, however, the parallel-configured hybrid vehicle uses much more gasoline and total energy than the reference baseline vehicle, even at $\gamma = 0$. As noted previously for the urban cycle, the bluff-shaped van is being compared with a more streamlined baseline vehicle, and the disadvantages of its larger aerodynamic drag are even more apparent at the higher speeds associated with the highway cycle.

S.4.2.4 Impact of Vehicle Weight

Energy consumption characteristics for the three vehicle weights were recast in an operational range format for the parallel configuration. Operational range for the series configuration need not be considered because it exceeds the energy consumption of the conventionally powered vehicle at all γ values.

Analysis results are illustrated in Figure S-28. Of the three vehicle weights, the 4000-lb car has the lowest energy consumption. It shows energy savings for all fuels below about 200 miles and below 265 miles for petroleum-based fuels. Commensurate values for the 2500-lb car are 115 and 150 miles. The 6000-lb van was included only for comparison since it exceeds the conventional vehicle energy consumption throughout the vehicle range shown.



*Fraction of battery recharge energy supplied by heat engine

FIGURE S-26. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

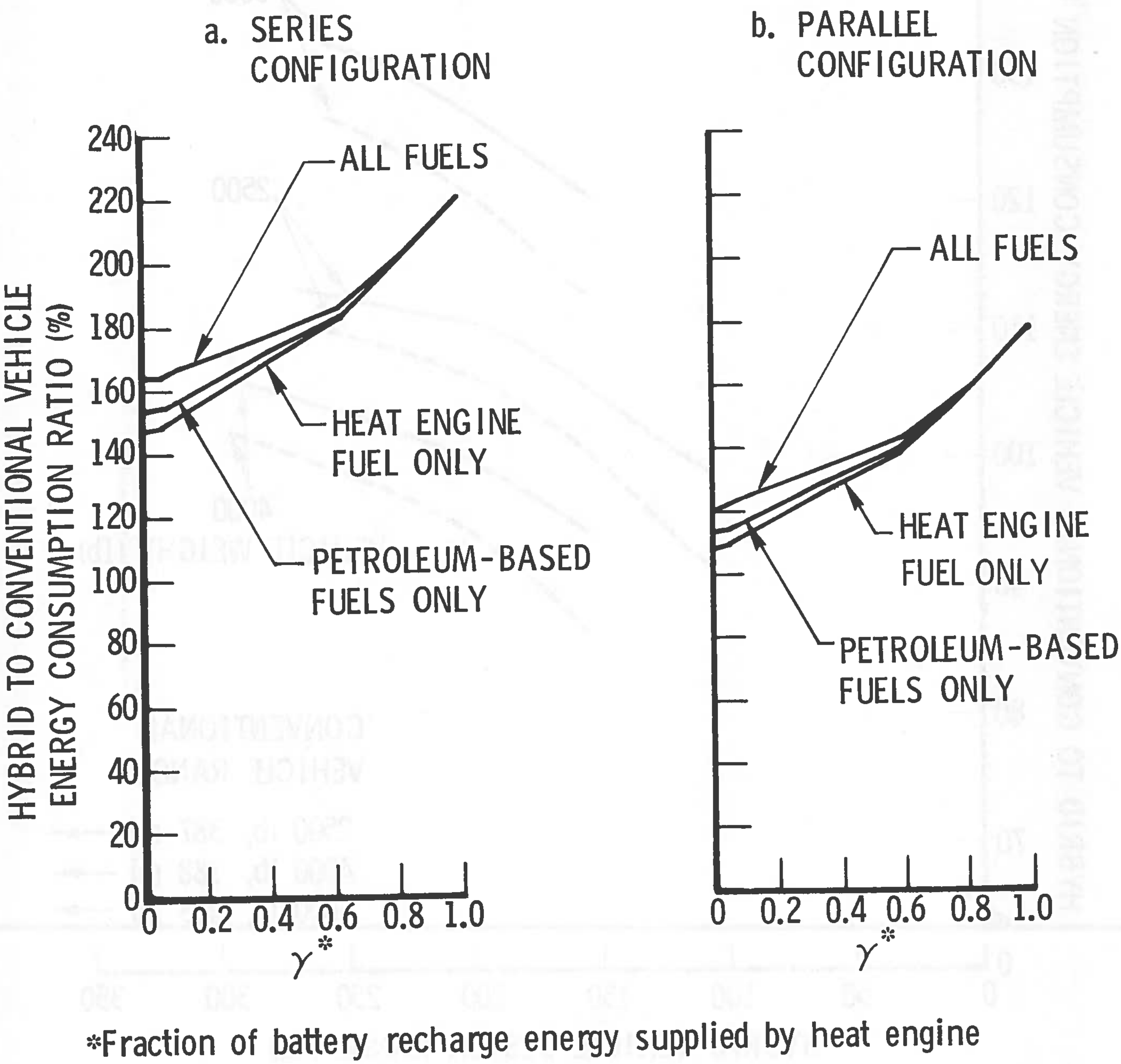


FIGURE S-27. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

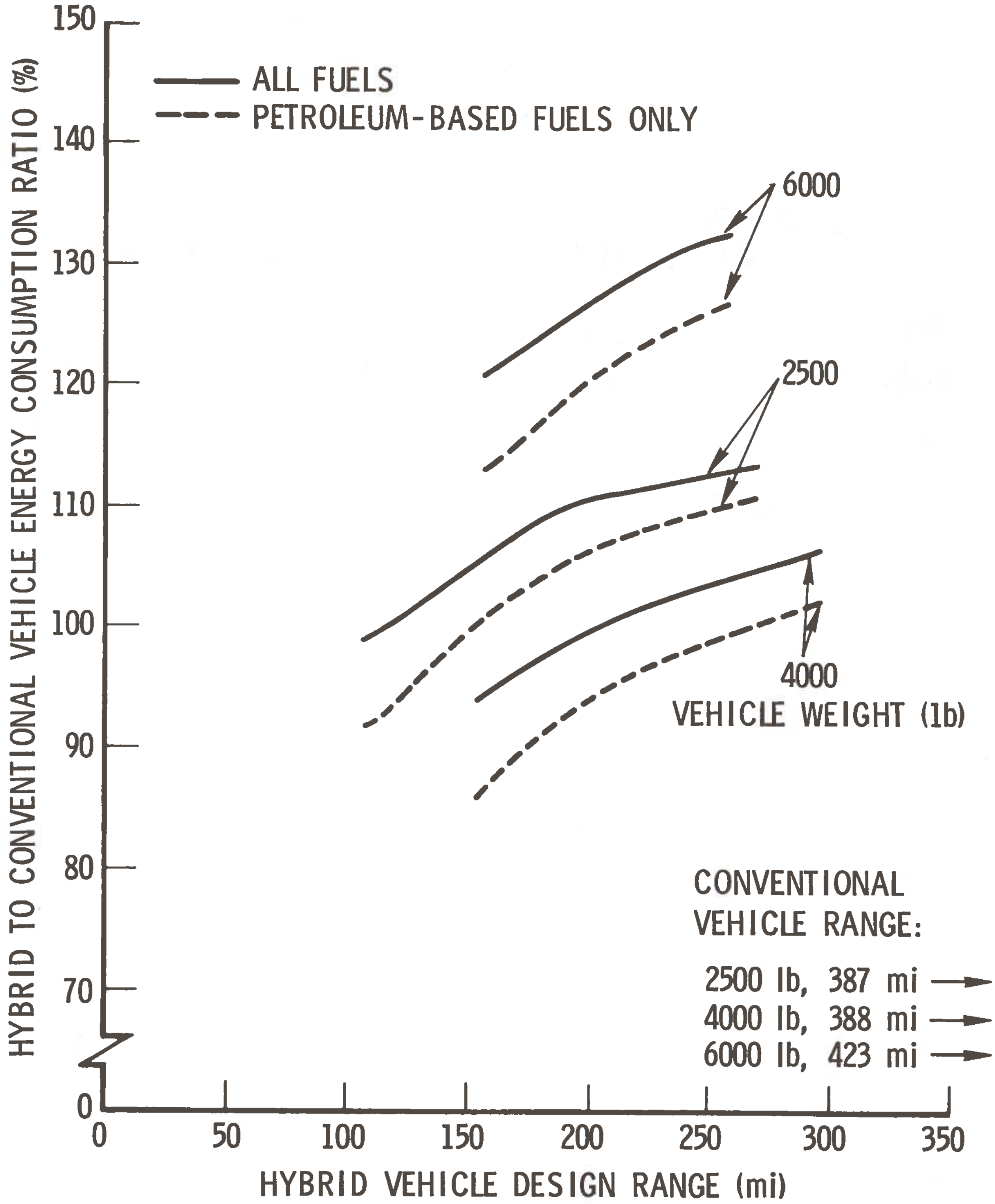


FIGURE S-28. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA HIGHWAY DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, PARALLEL CONFIGURATION

S.4.3 ENERGY CONSUMPTION CHARACTERISTICS FOR THE U.S. POSTAL SERVICE DRIVING CYCLE

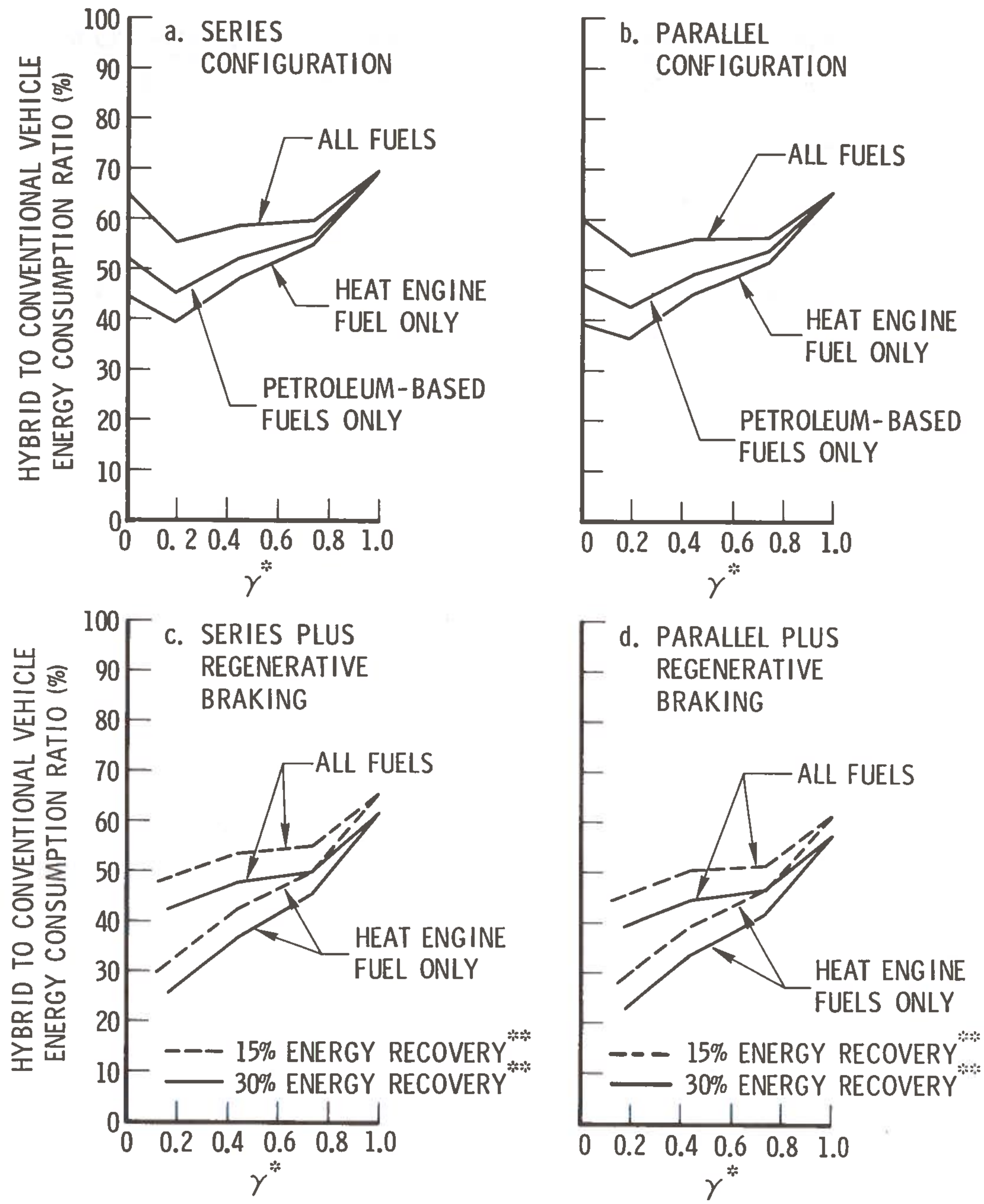
S.4.3.1 4000-lb Car

The fuel energy consumption characteristics of the 4000-lb heat engine/battery hybrid vehicle are depicted in Figure S-29 for operation over the U.S. Postal Service Driving Cycle. The energy consumption of the hybrid vehicle has been referenced to the gasoline energy consumption for a conventionally powered vehicle operated over the same cycle which, in lieu of road test data, was calculated to be 8.1 mpg or 4.15 kW-hr/mi (Table S-2).

As seen in Figure S-29a, the series configuration hybrid vehicle uses much less energy than the conventional car at all γ values. When the heat engine is used to provide all of the battery recharge energy, the series configuration consumes only about 70 percent of the gasoline required for powering the conventional car. As γ is reduced and more battery recharge energy is provided from an electrical outlet, the hybrid heat engine energy consumption continues to decline with a minimum of 40 percent gasoline required about $\gamma = 0.2$. This trend holds as well for the overall hybrid energy consumption (tanked onboard gasoline plus the recharge energy generated by fuel consumption at the electric generating plant) with a minimum of 55 percent energy consumption. The rise in energy consumption for lower γ values is due, as noted in the urban cycle discussion, to the onset of poor engine efficiency at very low engine power levels.

As seen in Figure S-29b, the more efficient parallel configuration results in additional energy savings. At 100 percent use of the onboard heat engine for battery recharge ($\gamma = 1.0$), about a 35 percent savings in gasoline is possible. Heat engine consumption decays to a minimum near $\gamma = 0.2$, as for the series configuration, with a possible savings of about 63 percent in gasoline and 47 percent savings in overall energy consumption.

Figures S-29c and S-29d illustrate the effect of regenerative braking on energy consumption for the series and parallel configurations, respectively. At $\gamma = 1.0$ and 30 percent recovery of vehicle drive wheel energy, the series configuration energy consumption decreases to 62 percent



*Fraction of battery recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in battery

FIGURE S-29. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

of that for the conventional car. Greater effects are seen as γ decreases. When no recharge energy is provided by the heat engine, γ decreases to no less than about 0.12 for 15 percent recovery and 0.17 for 30 percent recovery because of the continued introduction of regenerative braking energy into the battery. At this point, for 30 percent recovery, there are gasoline energy savings of as much as 74 percent and total energy savings of about 57 percent.

The parallel configuration displays very similar results with, at best, an incremental 4 percent additional savings over the series configuration.

S.4.3.2 2500-lb Car

The energy consumption characteristics of the 2500-lb heat engine/battery hybrid vehicle are illustrated in Figure S-30 for operation over the U.S. Postal Service Driving Cycle. Here, the basis of comparison is the gasoline energy consumption of the 2500-lb vehicle of Table S-2 (12.4 mpg or 2.72 kW-hr/mi). The basic effects of configuration (series compared with parallel) and of various degrees of regenerative braking are similar to those described for the 4000-lb car.

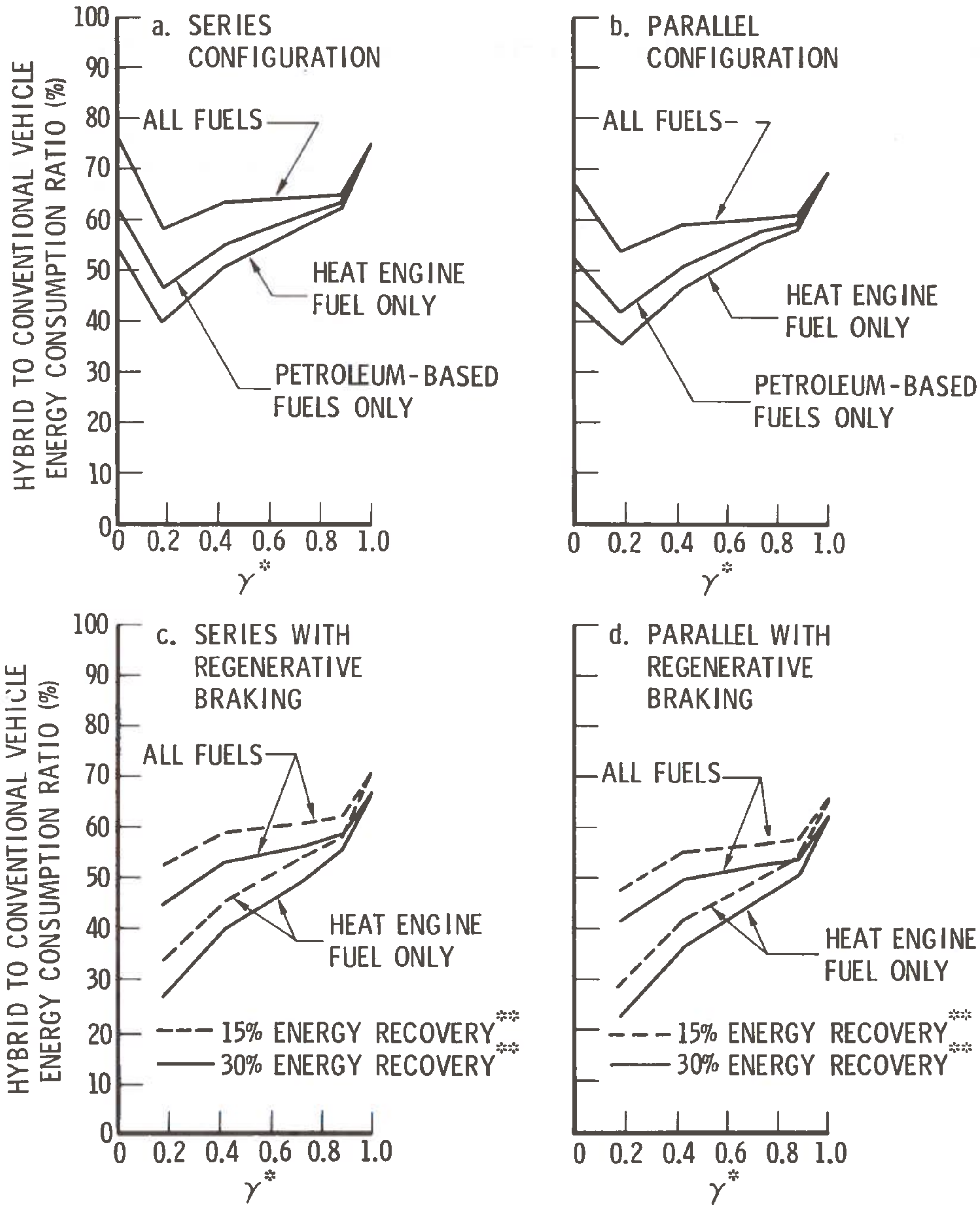
S.4.3.3 6000-lb Van

Figure S-31 depicts the energy consumption characteristics of the 6000-lb hybrid vehicle as compared with the gasoline energy consumption of the baseline vehicle of Table S-2 (5.3 mpg, or 6.34 kW-hr/mi). Again, the basic effects of configuration and of regenerative braking are similar to those described for the 4000-lb and 2500-lb hybrid vehicles.

S.4.3.4 Impact of Vehicle Weight and Regenerative Braking

Energy consumption for three series configuration vehicle weights is presented as a function of range in Figure S-32. The energy savings over a conventional vehicle are quite remarkable and, even at large operating range, the energy savings for all fuels is 35 to 40 percent.

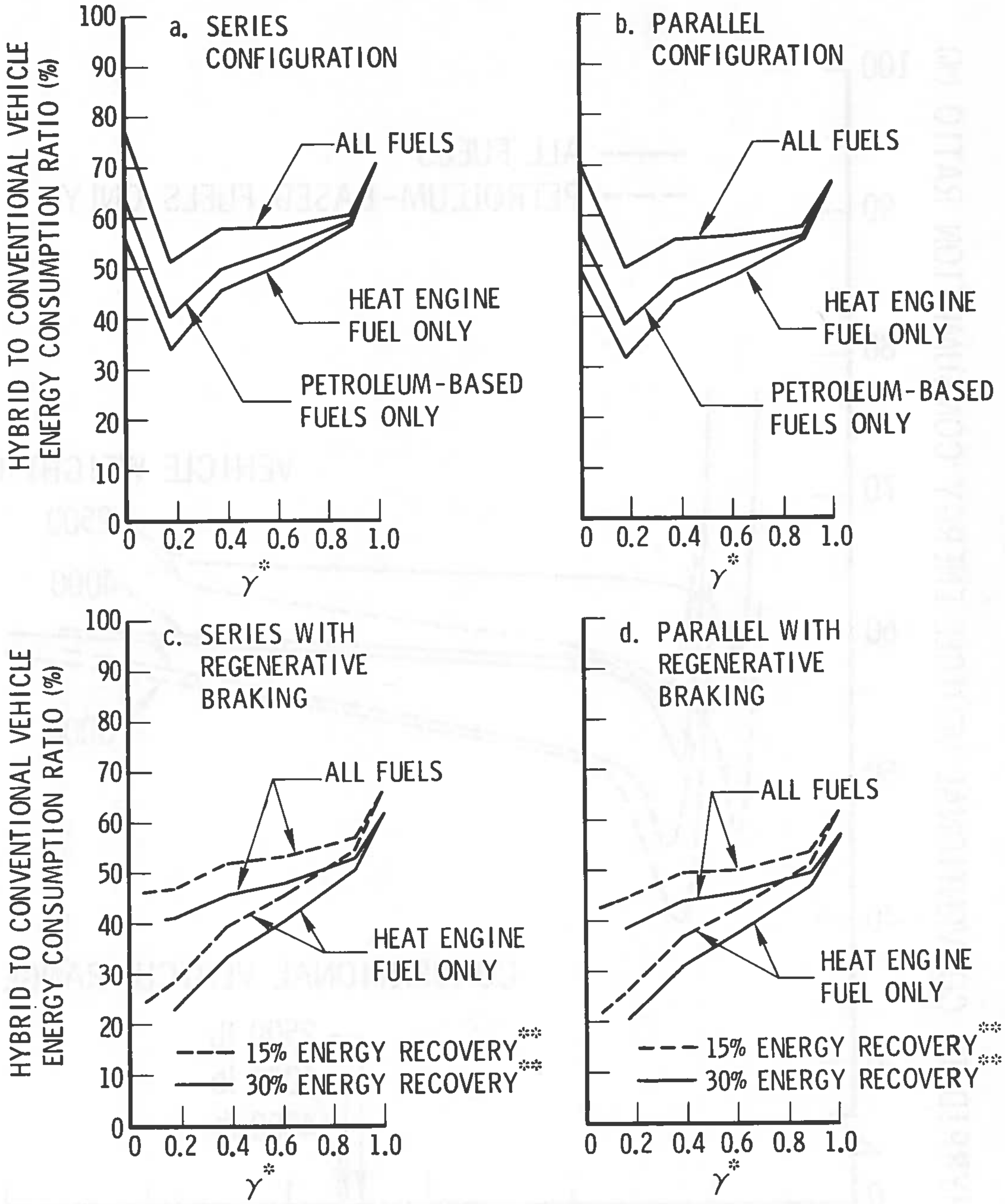
The additional savings possible by use of regenerative braking is shown in Figures S-33 through S-35 for the series configuration and S-36 through S-38 for the parallel configuration. With 30 percent recovery of



*Fraction of battery recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in battery

FIGURE S-30. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of battery recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in battery

FIGURE S-31. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

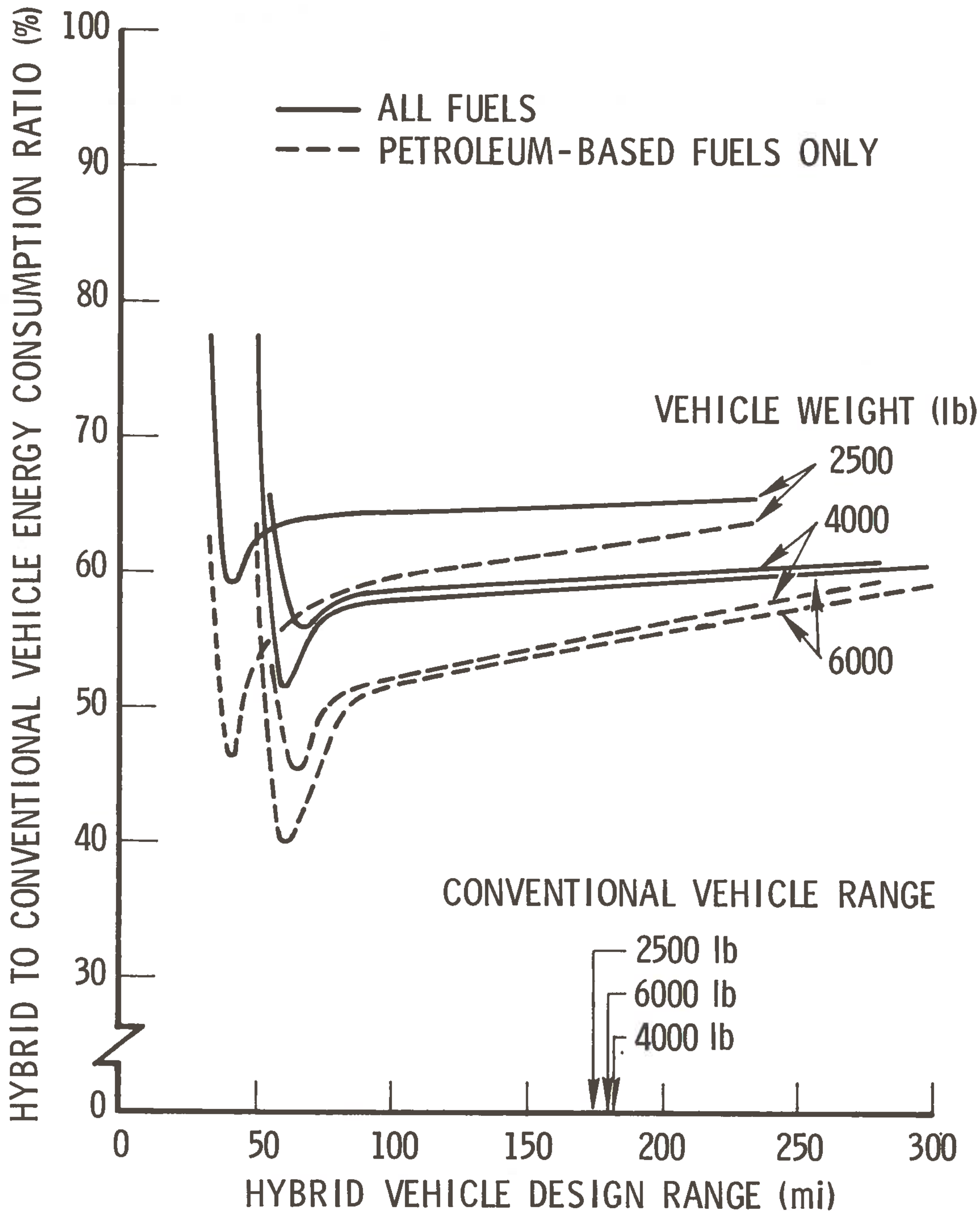


FIGURE S-32. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION

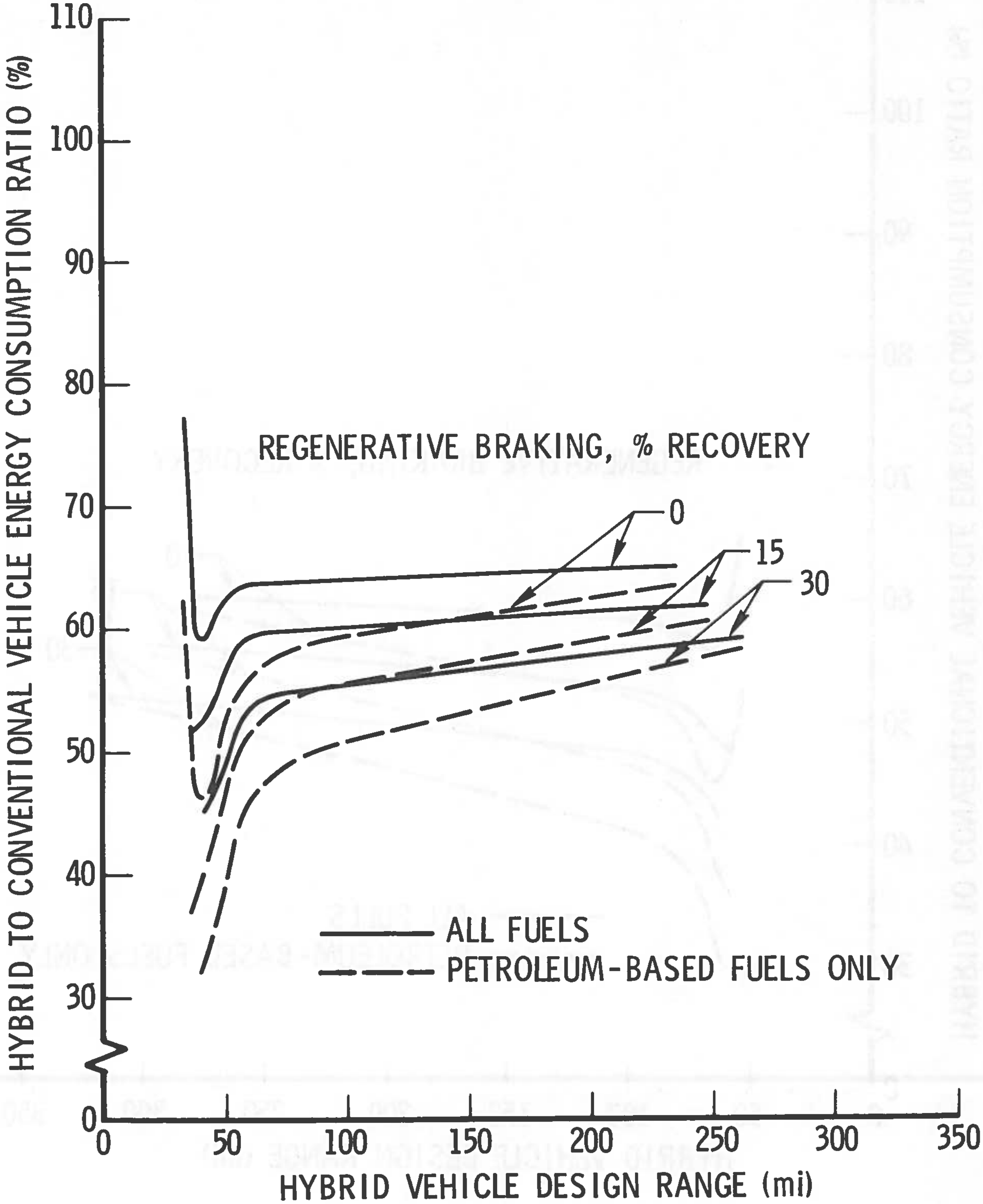


FIGURE S-33. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, SERIES CONFIGURATION

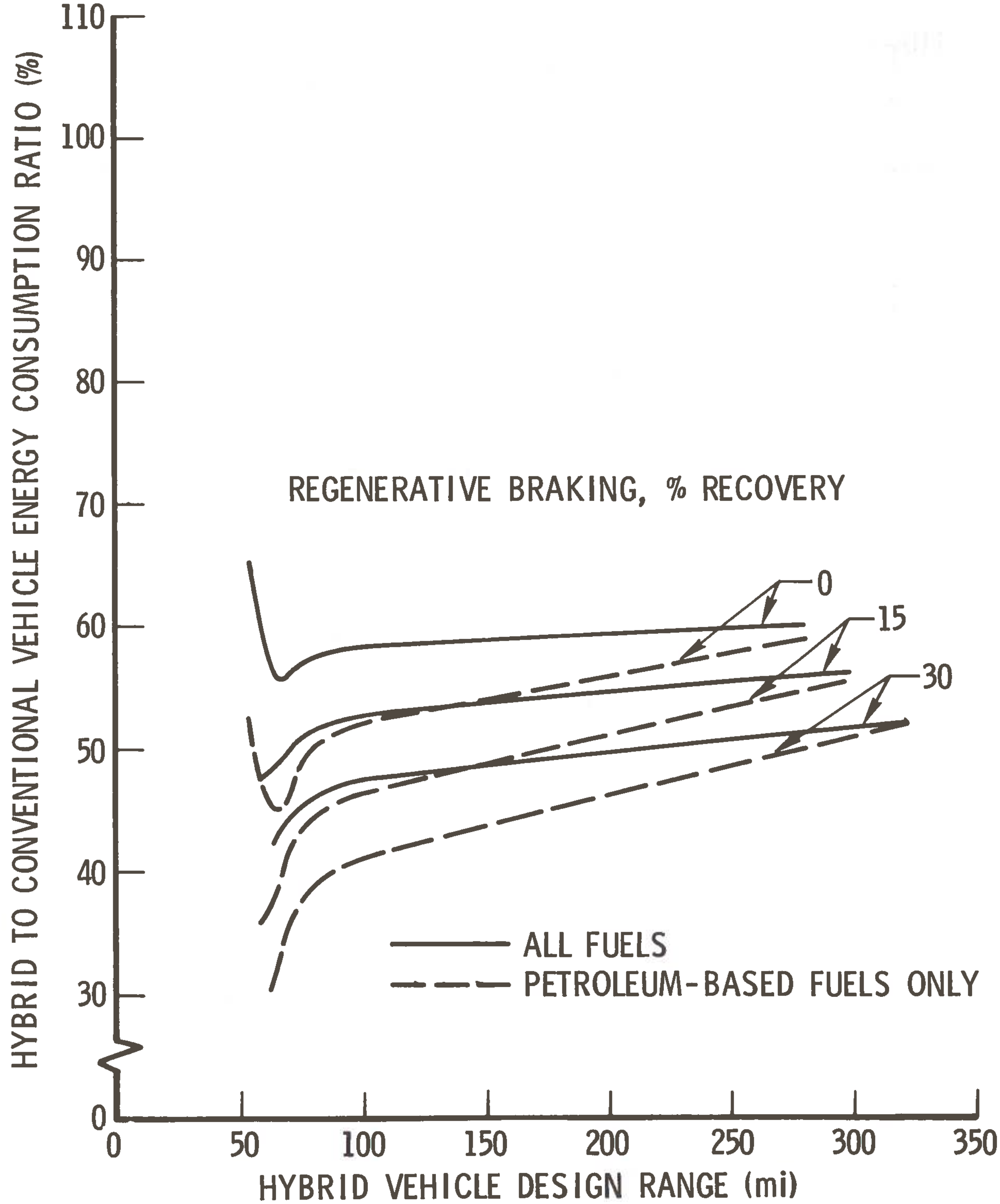


FIGURE S-34. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, SERIES CONFIGURATION

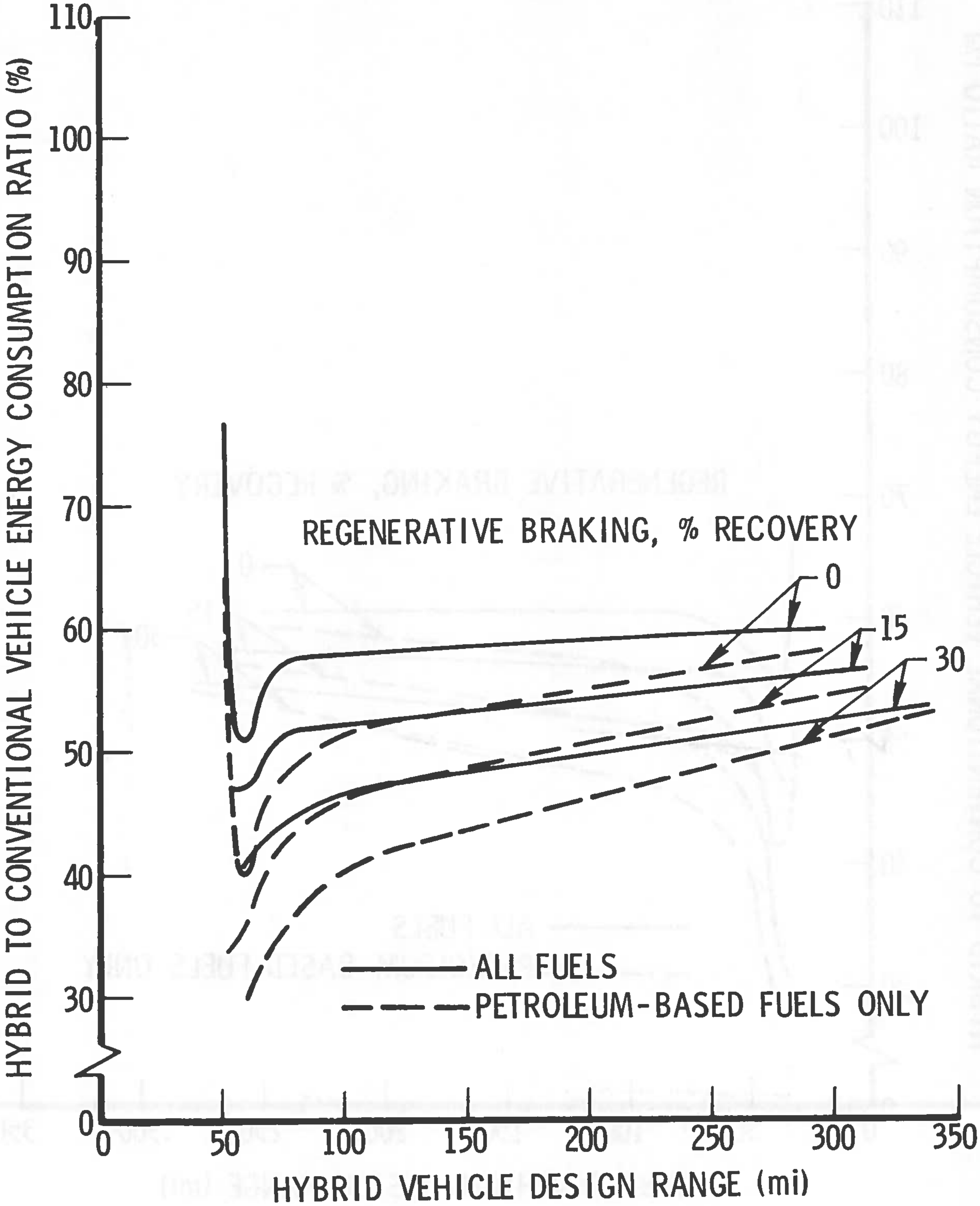


FIGURE S-35. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, SERIES CONFIGURATION

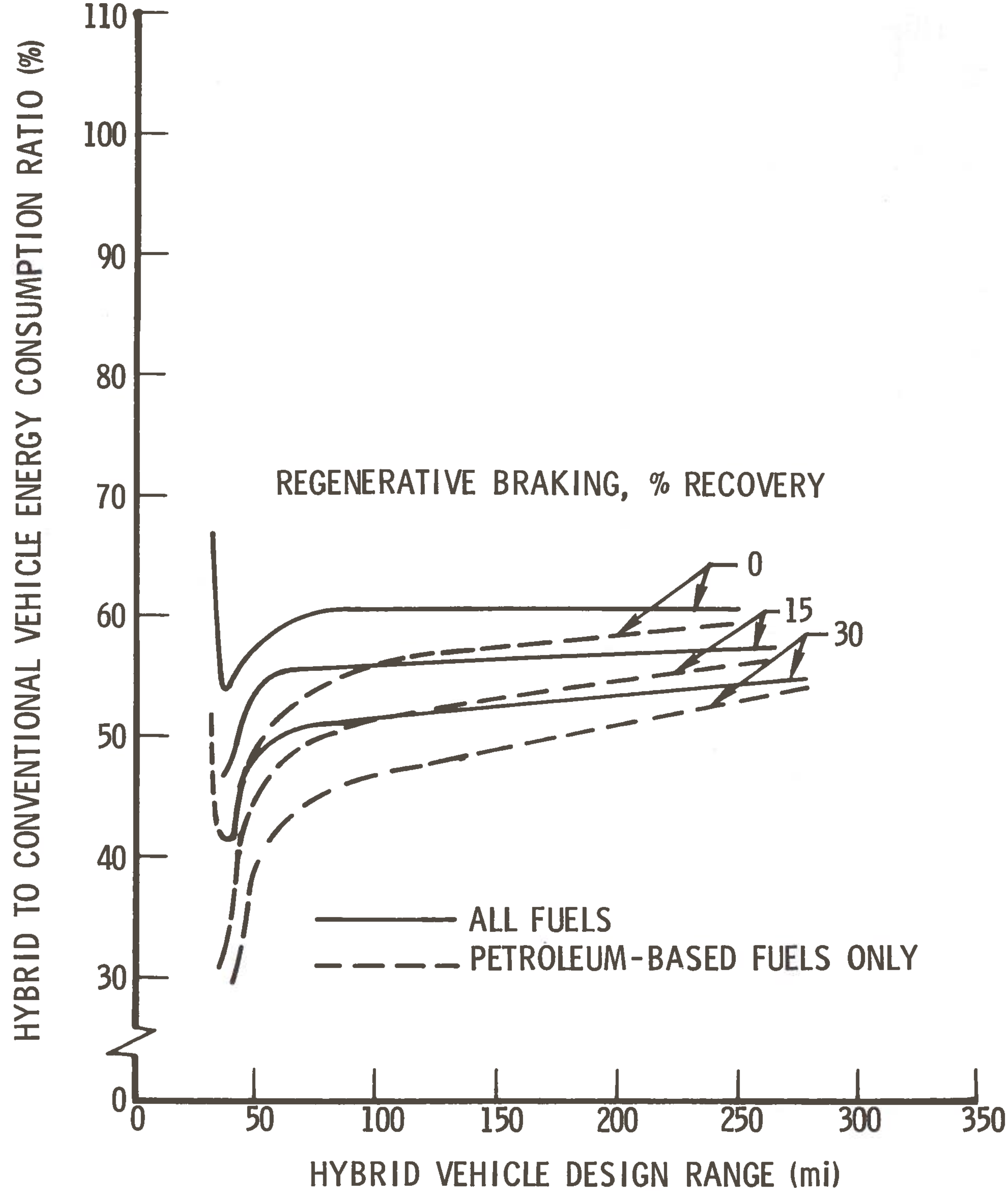


FIGURE S-36. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, PARALLEL CONFIGURATION

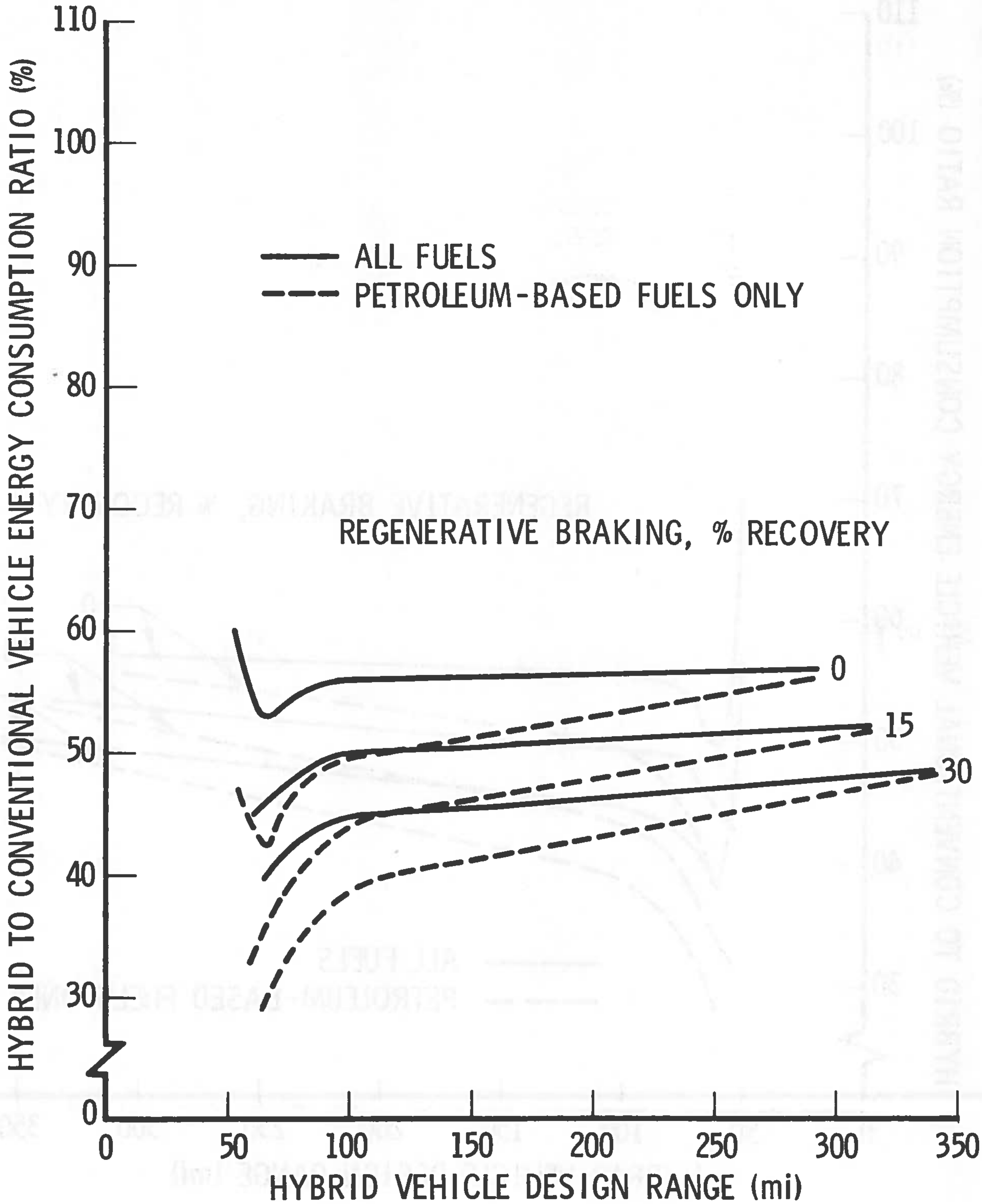


FIGURE S-37. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, PARALLEL CONFIGURATION

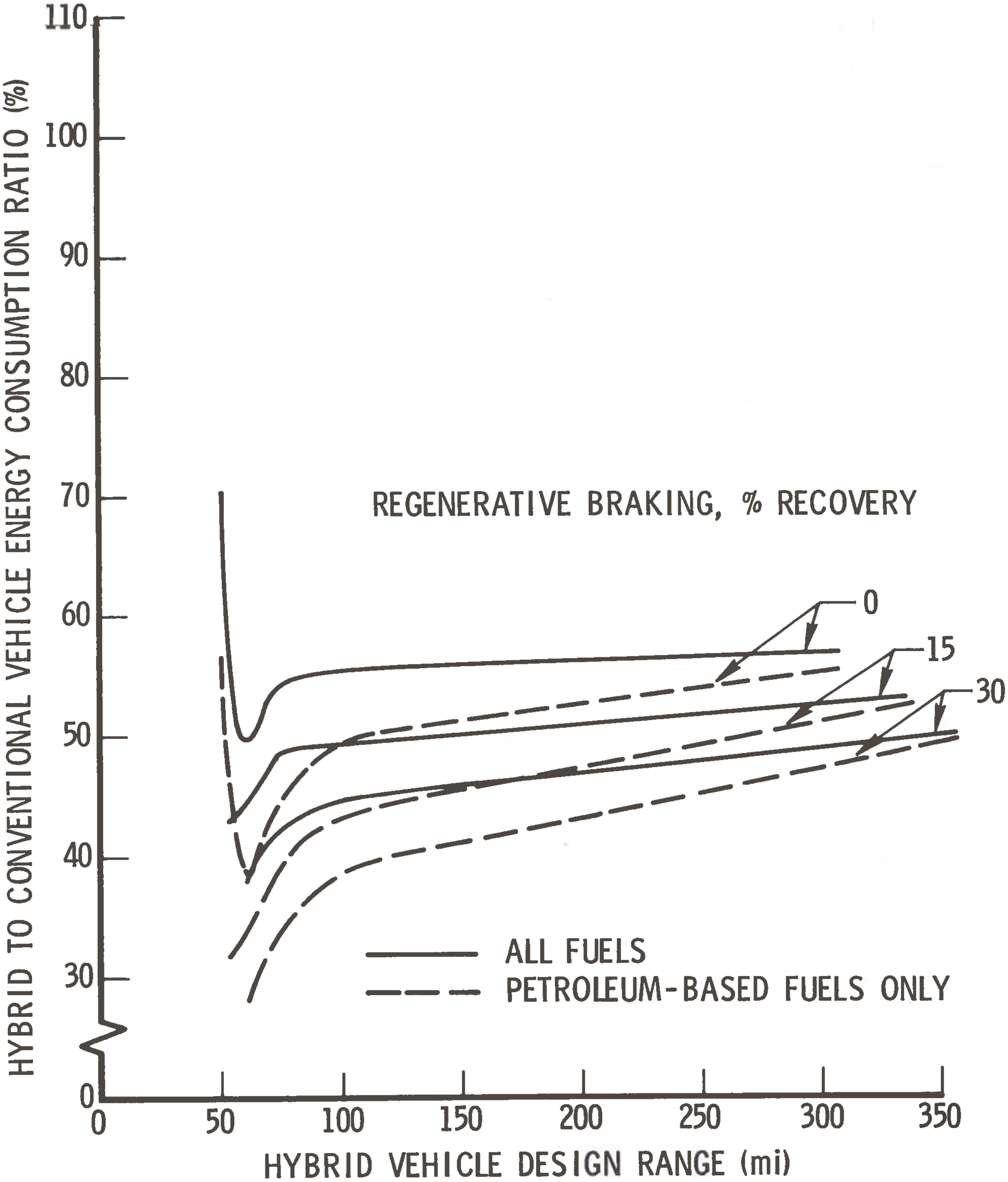


FIGURE S-38. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, PARALLEL CONFIGURATION vehicle drive wheel energy, the total energy consumption of the 4000-lb vehicle is less than half that of the conventional vehicle even at operating ranges exceeding 200 miles. For an operating range limited to about 100 miles, there is about a 60 percent savings in petroleum-based fuel.

The sharp rise in energy consumption at the lowest range is due to the very low engine power operation producing a very rapid rise in BSFC and, therefore, higher than normal fuel consumption. The same effect was seen in the urban cycle, but to a lesser degree.

The major advantage of the hybrid vehicle over the conventionally powered vehicle for the type of stop-and-go driving characterized by the postal cycle is very evident. In contrast to the highway cycle, the conventionally powered vehicle powertrain here is operating at very low efficiencies. In addition, there is the problem of idle fuel consumption of a large engine. Hence, it would seem that an excellent application of the hybrid vehicle concept would be to delivery cars, vans, or trucks with operating range requirements that exceed the capabilities of all-electric powertrains.

S.4.4 EXHAUST EMISSION CHARACTERISTICS

Vehicle-related exhaust emissions of HC, CO, and NO_x were determined for the 2500-lb and 4000-lb car weights and for the 6000-lb van operating over the EPA Urban Driving Cycle. The emissions are expressed as a percentage of the 1975-76 federal emission standards for light-duty vehicles. (Emissions are not of critical importance for hybrid vehicle evaluation on the highway and postal cycles simply because there are no government standards to be met for these cycles, and, therefore, no such discussion is included in this section.)

The emissions are presented for the series configuration in Figures S-39 and S-40 as a function of vehicle design operational range. Figure S-39 shows the effect of vehicle design cruise speed as vehicle weight is fixed at 4000 pounds. The highest emissions are produced by a 55-mph design cruise speed vehicle, and the lowest emissions are generally shown by the 80-mph vehicle. This effect is just the reverse of the order shown for energy consumption previously. Figure S-40 shows the effect of vehicle

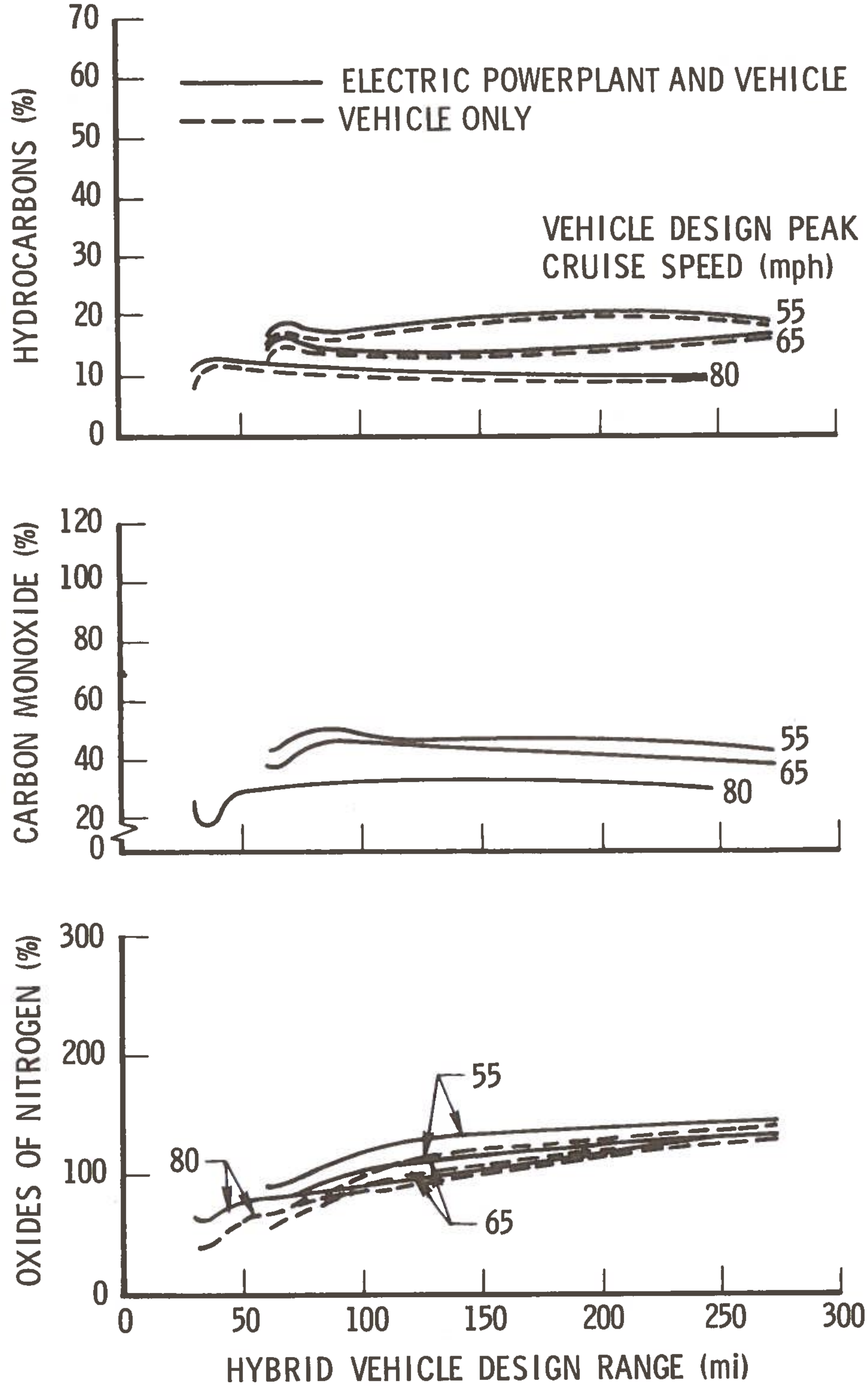


FIGURE S-39. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE WEIGHT = 4000 LB, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

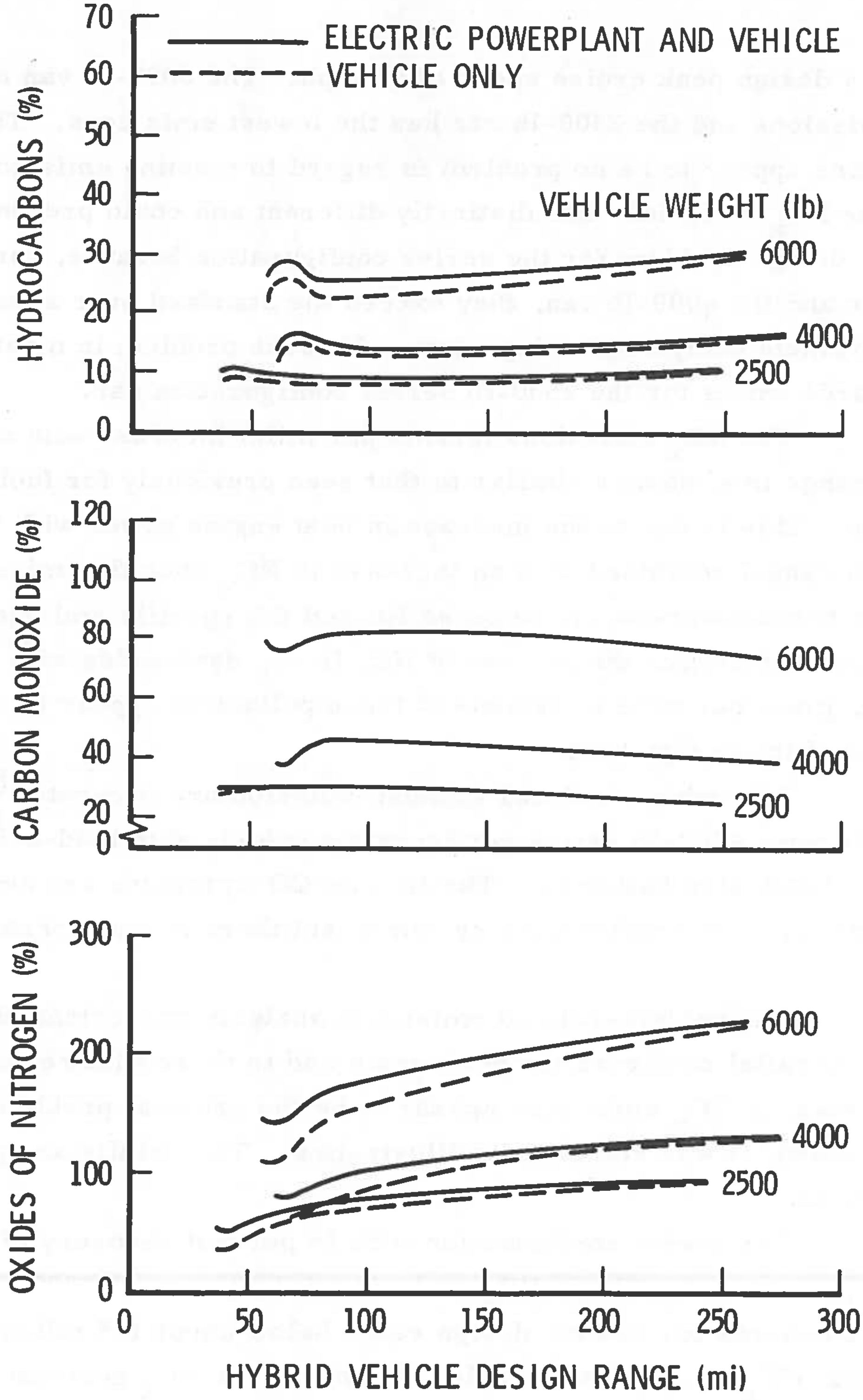


FIGURE S-40. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS) weight for a design peak cruise speed of 65 mph. The 6000-lb van has the highest emissions and the 2500-lb car has the lowest emissions. The HC and CO emissions appear to be no problem in regard to meeting emission standards. The NO_x emissions are distinctly different and could present a critical vehicle design problem for the series configuration because, for the 4000-lb car and the 6000-lb van, they exceed the standard over a substantial portion of vehicle design operating range. No such problem in meeting emission standards exists for the 2500-lb series configuration car.

The NO_x emissions (grams per mile) increase with design operating range in a manner similar to that seen previously for fuel energy expenditure. This is due to the increase in heat engine power with γ (and, hence, with range) combined with an increase in NO_x specific emissions (grams per horsepower-hour). Because HC and CO specific emissions generally have characteristics the inverse of NO_x (i.e., decreasing with increasing power), gram per mile emissions of these pollutants appear to be almost independent of the design range.

The vehicle-related exhaust emission are presented in Figure S-41 for a 4000-lb series configuration vehicle with lead-acid batteries in place of nickel-zinc batteries. The HC and CO emissions are not changed to any degree from the nickel-zinc systems, but there is a noticeable increase in NO_x.

The vehicle-related emissions analysis was extended to vehicles with parallel configuration powertrain and to those with regenerative braking. Because NO_x emissions appear to be the greatest problem in meeting the standard, it was selected for illustration. The results are presented in Figure S-42.

The series configuration with 15 percent recovery of drive wheel energy shows significant NO_x emission reductions. A 4000-lb car meets the standards for vehicle design range below about 155 miles when considering total NO_x emissions and below 200 miles for NO_x generated solely by the hybrid vehicle. For total NO_x emissions, the 6000-lb van continues to exceed the standard for all values of design operating range; the 2500-lb car is well below the emission standard.

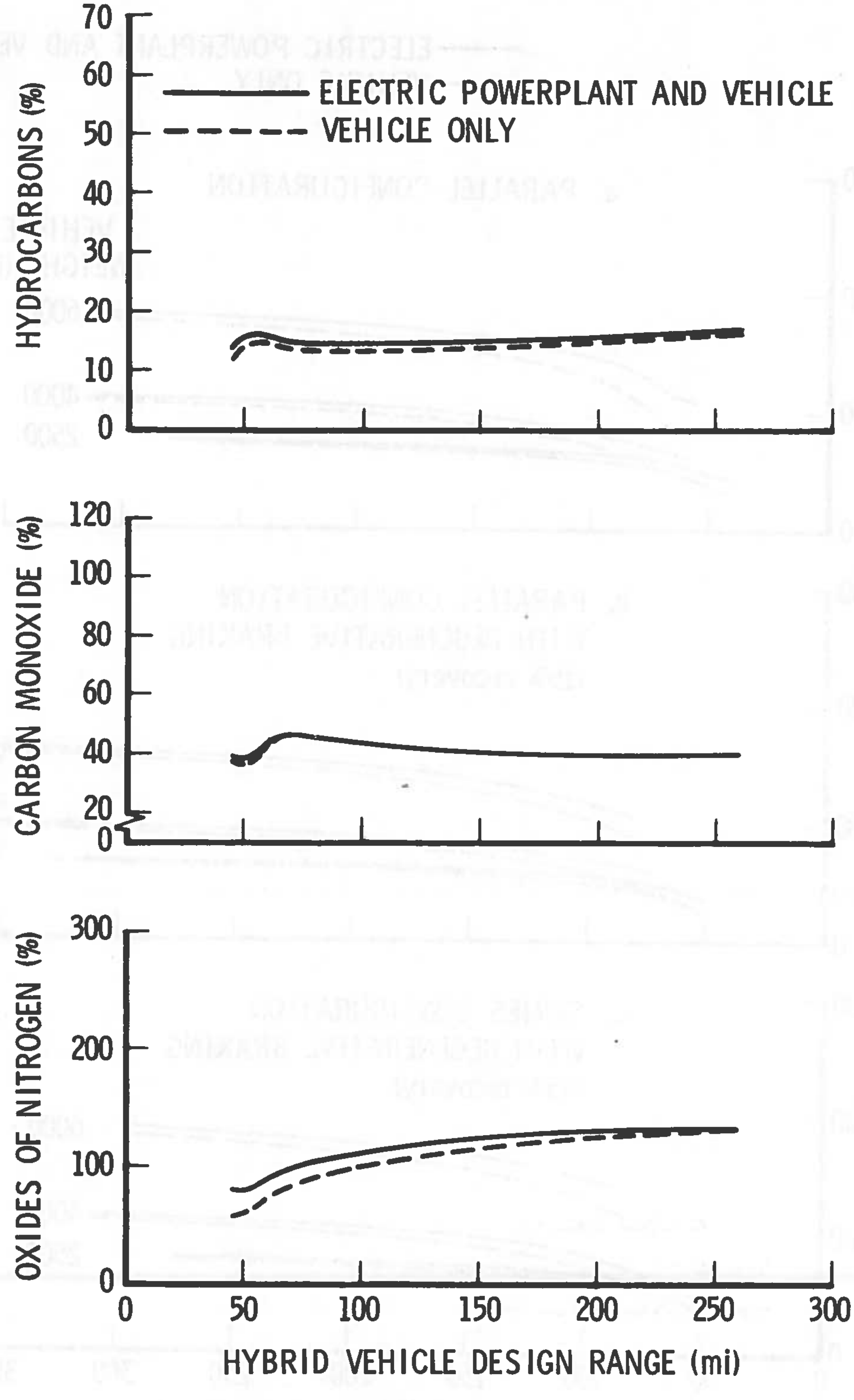


FIGURE S-41. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, LEAD-ACID BATTERY SYSTEM, VEHICLE WEIGHT = 4000 LB, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

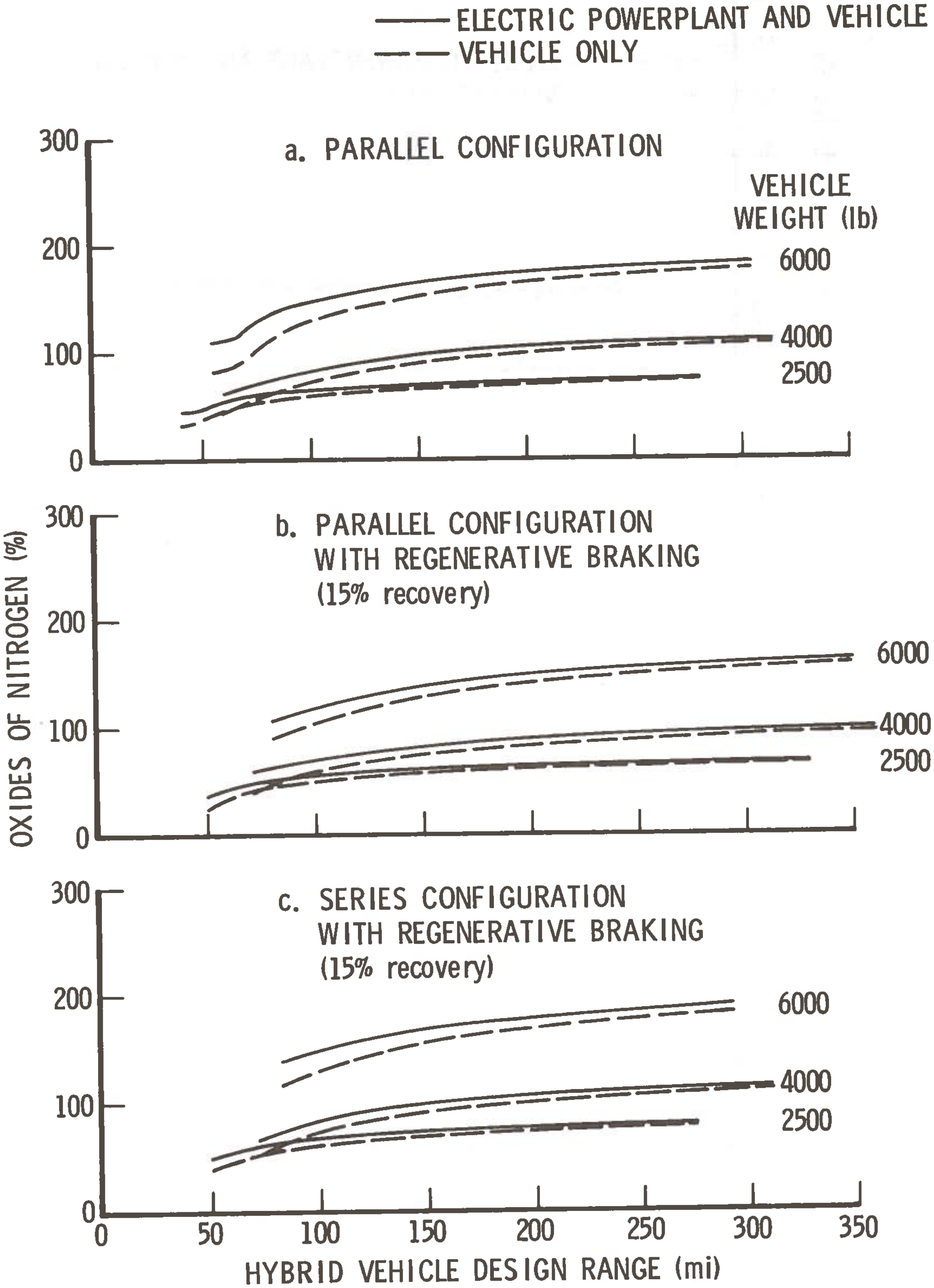


FIGURE S-42. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED NO_x EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH (REF.: 1975-76 FEDERAL STANDARDS)

Very similar effects are seen for the parallel configuration without regenerative braking. For the 4000-lb car, the NO_x emission standard is met at a vehicle design range below 160 miles for all emission sources and below 210 miles for emissions from only the hybrid vehicle. With 15 percent recovery of drive wheel energy, the 4000-lb car meets the standard for all values of design operating range. The 6000-lb vehicle, however, continued to exceed the standard except for vehicle-only emissions at the very lowest design operating range.

Because power plant sources contribute only a small fraction of the overall vehicle-related exhaust emissions, regional characteristics are not expected to have any major impact on the emission levels previously presented. A favorable emission reduction would be expected for the Pacific Northwest that relies so heavily on the relatively pollution-free hydroelectric power. In this case, the "vehicle only" curves would apply, regardless of the degree of reliance on electric generating plants for recharge energy.

The emission and energy consumption trends show a clear proportionality to vehicle weight. This is certainly expected, because these parameters are proportional to engine power output, which is, in turn, proportional to vehicle weight. Vehicle weight appears to have a much stronger impact on emissions than on energy consumption, but this is only because the reference emission standards are fixed, whereas the reference energy consumption varies with vehicle weight. In addition, the very high NO_x emission levels of the 6000-lb van are also due to the higher drag of the van, which requires that greater power be delivered to the drive wheels.

Some NO_x emission reduction could be expected by operating the heat engine with a revised schedule of power as a function of rpm, but this would likely result in an increase in fuel energy expenditure and a possible increase in HC and CO emissions. Since the HC and CO emission levels are already well below the standards, the increase may not be of great concern. A similar tradeoff between emissions and energy consumption could also be effected by installing a larger engine that would then operate at lower part-load values.

Overall, though, the NO_x emissions are expected to be a factor possibly limiting the design operating range of hybrid heat engine/battery vehicles, regardless of the engine power-rpm schedule selected. The larger and heavier vehicles would be expected to have the greatest limitations on range, whereas compact and subcompact vehicles should be relatively free of such problems. These results are, of course, based on the particular heat engine operating map used in this study. Obviously, much design effort would be required to match a particular engine to a given vehicle design and mission in order to arrive at the lowest possible combination of vehicle-related emissions and fuel energy consumption.

S.5 HYBRID HEAT ENGINE/FLYWHEEL SYSTEM RESULTS

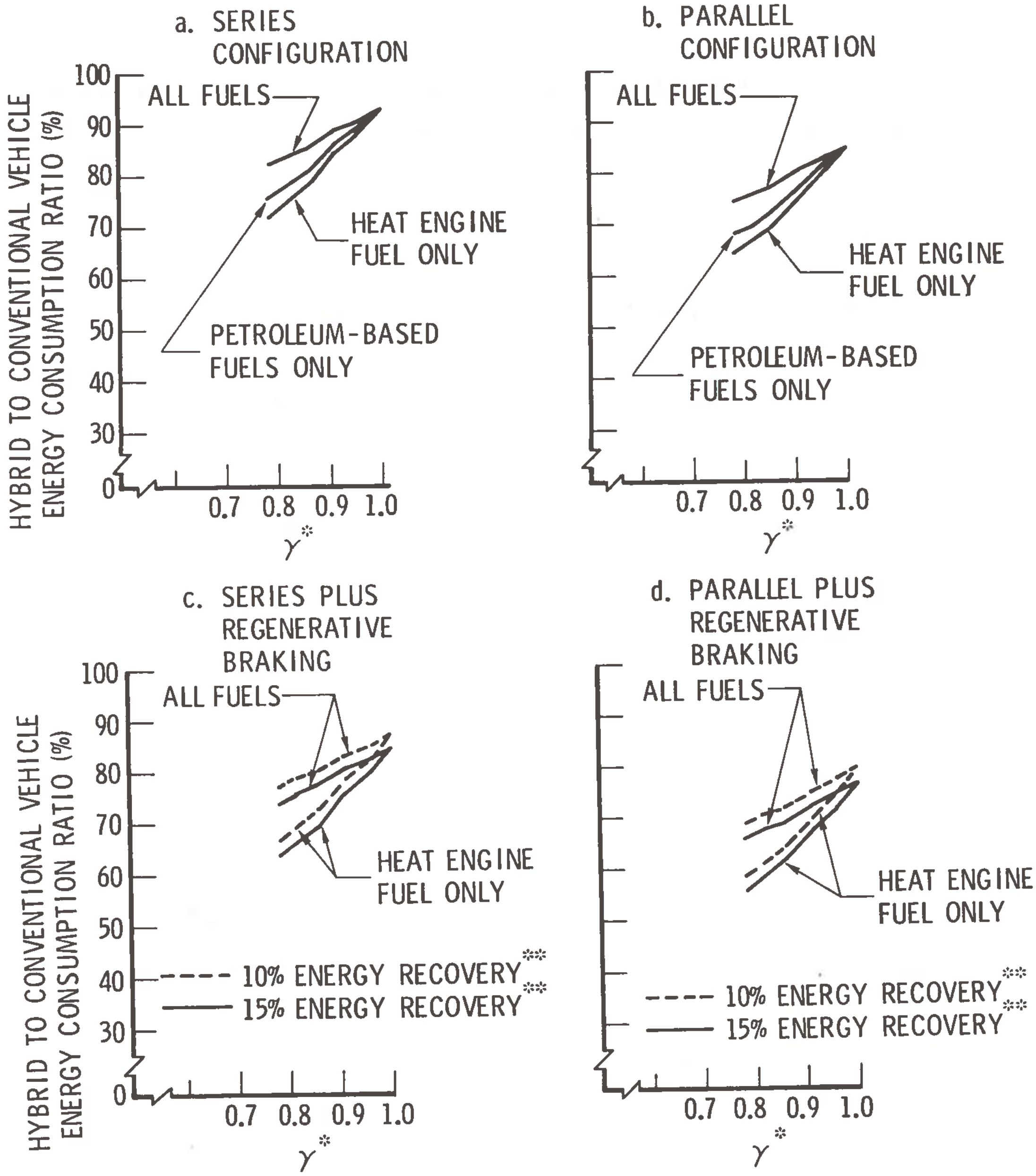
Analysis results for the flywheel system are presented in a format very similar to that used for the battery system. However, because the energy storage capacity of the steel flywheel is much less than the nickel-zinc battery, small reductions in the fixed minimum power setting of the heat engine from that needed to give 100 percent recharge of the flywheel results in large reductions in allowable vehicle design operating range. This effect tends to produce curves that show relatively invariant levels of energy consumption as the vehicle design operating range is varied. Hence, to more clearly show trends for the analysis results most of the energy consumption curves are presented with γ as the independent variable, rather than vehicle design range.

Energy consumption characteristics are compared for series and parallel powertrain configurations having different amounts of recovered regenerative braking energy. Three vehicle weights are examined for vehicle operation on three different driving cycles. In all cases, the energy consumption of the hybrid vehicle is referenced to the gasoline energy consumption of the baseline, conventionally powered vehicle operated over the same cycles. The impact of design peak cruise speed and exhaust emission characteristics are also discussed.

S.5.1 ENERGY CONSUMPTION CHARACTERISTICS FOR THE EPA URBAN DRIVING CYCLE

S.5.1.1 4000-lb Car

Analytical results giving the ratio of hybrid vehicle energy consumption to conventionally powered vehicle energy consumption are given in Figure S-43 as a function of γ (the fraction of flywheel recharge energy supplied by the heat engine or by the heat engine plus regenerative braking). The effect of regenerative braking is illustrated for energy recovery values of 0, 10, and 15 percent. In contrast to the hybrid heat engine/battery system, the flywheel system exhibits four primary differences: (a) at equivalent values of γ, the relative energy consumption is less, (b) for the series



*Fraction of flywheel recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in flywheel

FIGURE S-43. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

configuration without regenerative braking, the energy consumption is less than for a conventionally powered car at all γ values, (c) the range of γ is considerably less than for the battery system because all energy supplied by the heat engine passes through the flywheel and all energy to the vehicle drive wheels is delivered by the flywheel, and (d) the decrease in energy consumption of the parallel configuration, when compared with the series configuration, is not as noticeable as it was for the battery system because the series flywheel system has a high powertrain efficiency, and further improvements brought about by parallel designs have less impact.

The series configuration, shown in Figure S-43a, consumes about 93 percent of the fuel used by a conventionally powered car when the heat engine on board the hybrid car provides all of the flywheel recharge energy ($\gamma = 1.0$). This results from a combination of high efficiency elements in the powertrain and a heat engine operating near maximum efficiency. In Figure S-43b, the parallel configuration operating at $\gamma = 1.0$ shows about 85 percent of the fuel consumption of a conventionally powered car. When regenerative braking is included in the powertrain system, the series configuration at $\gamma = 1.0$ shows about 87.5 and 84.5 percent relative fuel consumption for 10 and 15 percent drive wheel energy recovery, respectively (Figure S-43c). Comparable results for the parallel configuration with regenerative braking are 79.5 and 76.5 percent.

Greater fuel savings are possible as γ is reduced from 1.0, but there is an accompanying sharp reduction in operating range. The flywheel system operating at γ values less than about 0.98 experiences complete exhaustion of stored energy within a vehicle travel distance as short as 25 miles. This results from the small energy storage capability of the steel flywheel. Therefore, the heat engine on the flywheel system must always continue to provide recharge energy to the flywheel to prevent rapid decay in its speed. Because of the necessity for this type of operation, the prospect of relying on electric generating stations for recharge energy need not be a consideration in the implementation of this type of hybrid vehicle. Similar performance is given by the parallel configuration and those systems using regenerative braking.

S. 5. 1. 2 2500-lb Car

Results for this vehicle are presented in Figure S-44 and are seen to be almost identical to those for the 4000-lb car. At $\gamma = 1.0$, the series configuration hybrid fuel consumption is 93 percent of the fuel consumed by a conventionally powered car (Figure S-44a). The greatest fuel savings are again shown by the parallel configuration with 15 percent recovery of drive wheel energy. As shown in Figure S-44d, its relative energy consumption is only 77 percent at $\gamma = 1.0$.

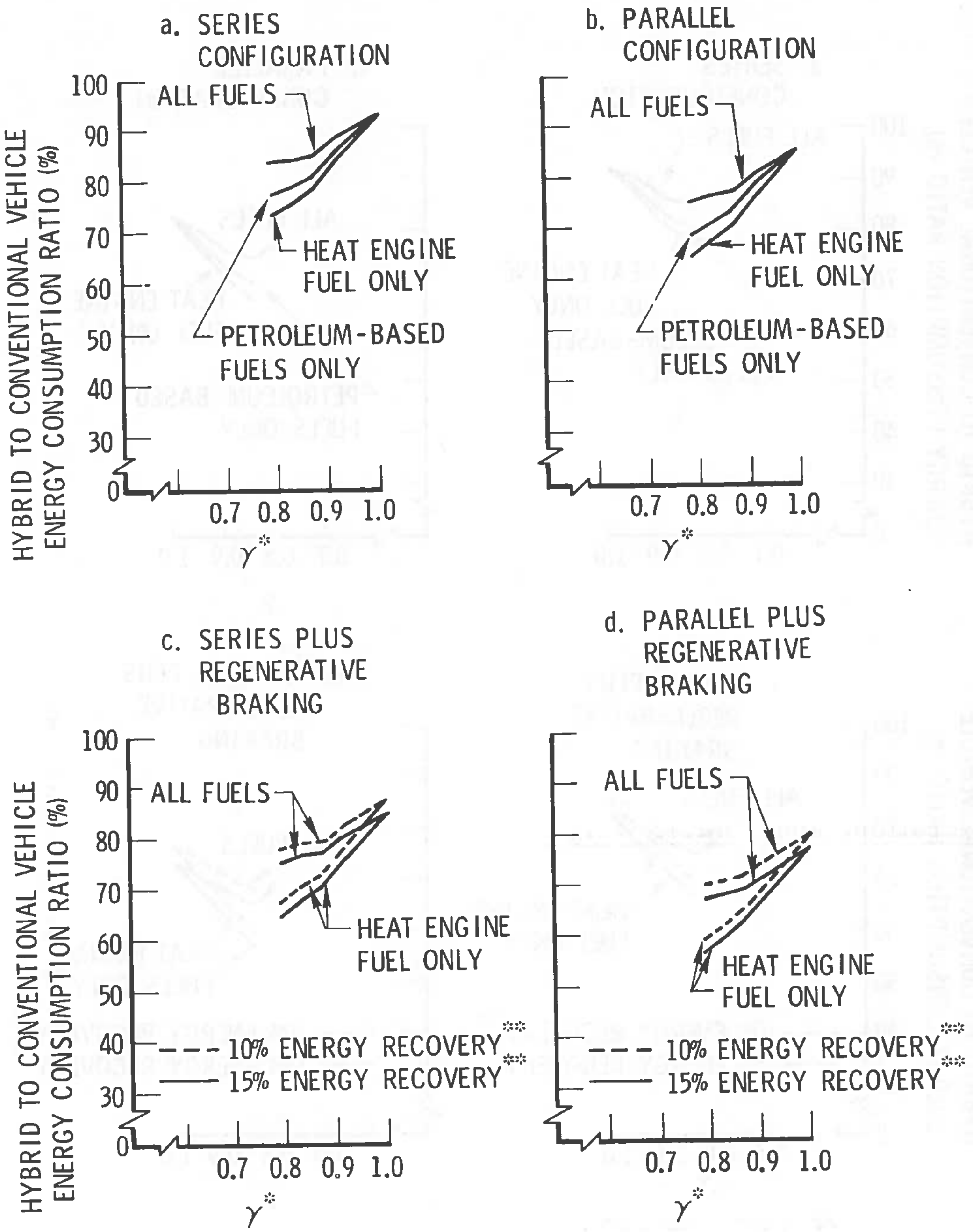
S. 5. 1. 3 6000-lb Van

Slightly lower values for energy expenditure are shown by the van in Figure S-45. At $\gamma = 1.0$, the series configuration uses 92.5 percent of the fuel consumed by a conventionally powered van. This consumption decreases to 73.5 percent, as seen in Figure S-45d, for the parallel configuration with 15 percent driving cycle energy recovered and the onboard engine providing all recharge energy.

S. 5. 1. 4 Impact of Design Peak Cruise Speed, Design Peak Acceleration, and Vehicle Weight

To show parametric effects, analytical results for the series configuration were plotted as a function of vehicle design operating range and are presented in Figure S-46. An increase in vehicle design cruise speed results in a decrease in the relative energy consumption, but the change is quite small. The effect of vehicle weight is even less discernible. It is also seen that the high efficiency of this system provides slightly greater maximum design operating range than for equivalent weight conventionally powered cars. Although not illustrated, there was no apparent effect of vehicle design acceleration on powertrain efficiency, and, hence, no effect on energy consumption.

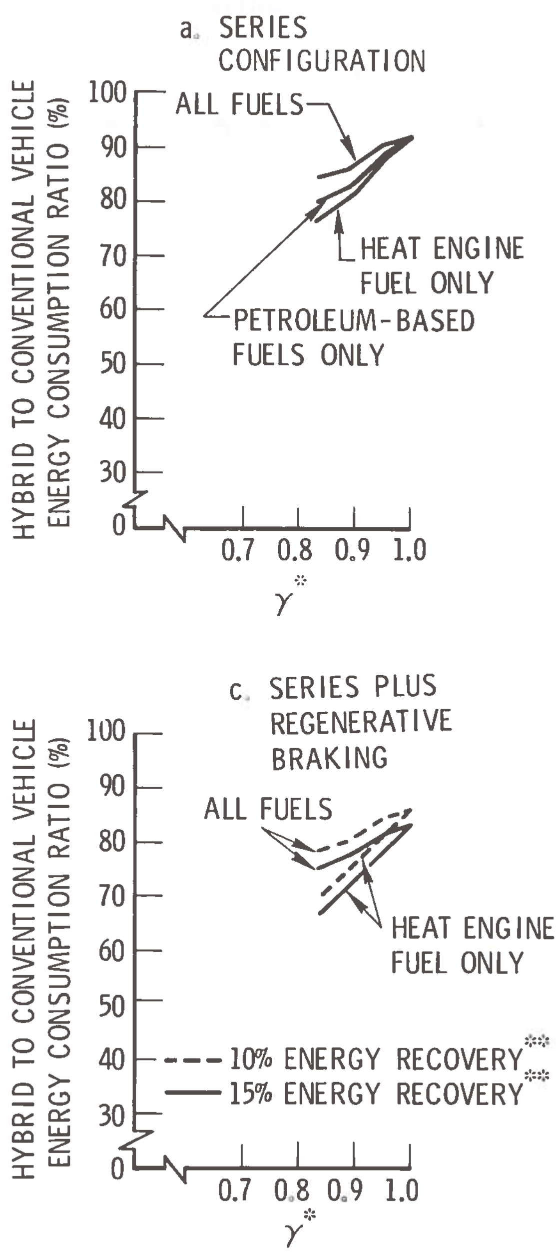
For the case of all fuels, energy savings of 6 to 11 percent are possible over a wide selection of values for vehicle design operating range. With consideration of only petroleum-based fuels, additional energy savings are evident for the most part only at a design operating range of less than 50 miles. Hence, in contrast to the heat engine/battery system, the heat



* Fraction of flywheel recharge energy supplied by heat engine, or by heat engine plus regenerative braking

** Percent of total driving cycle energy recovered and stored in flywheel

FIGURE S-44. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of flywheel recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in flywheel

FIGURE S-45. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

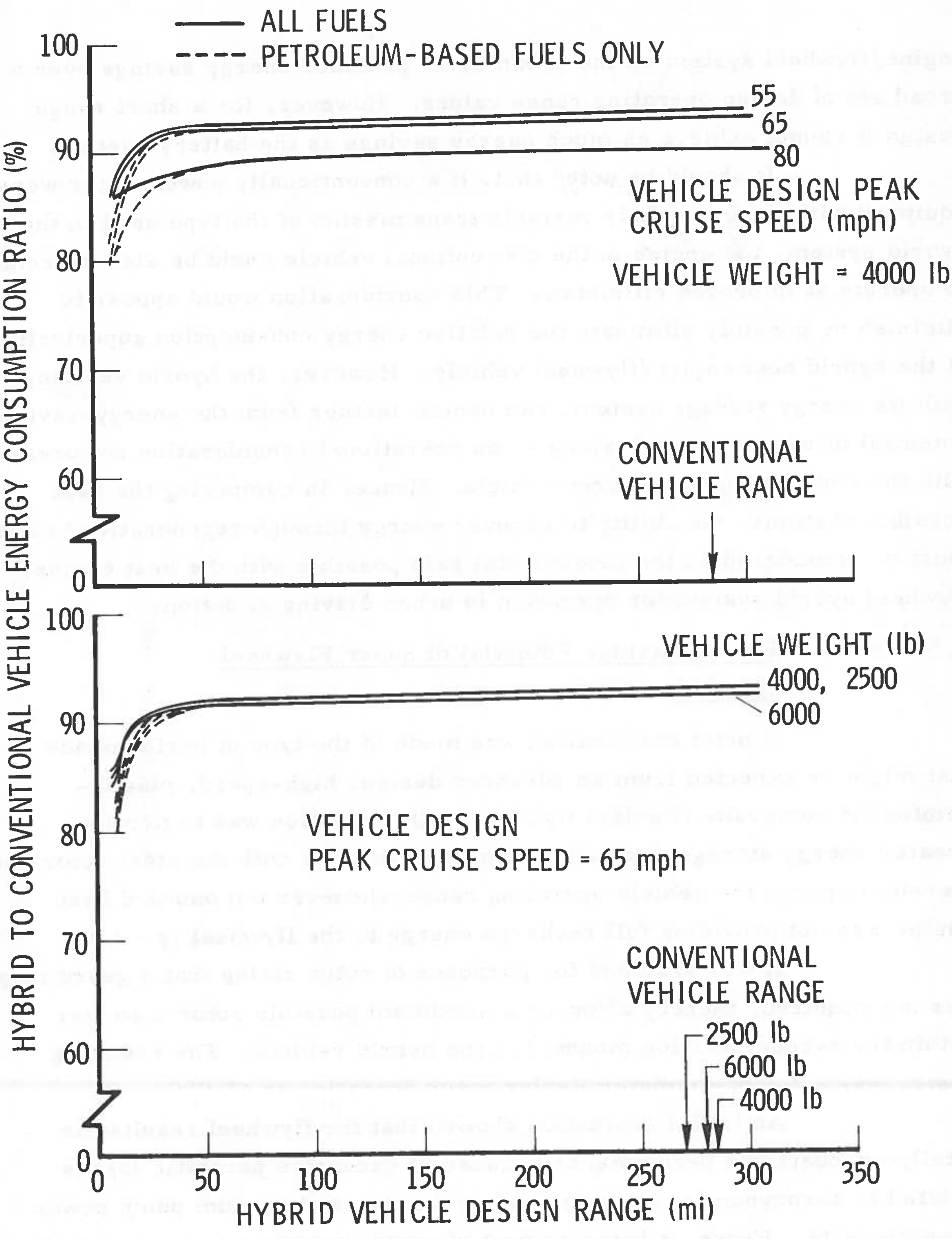


FIGURE S-46. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, SERIES CONFIGURATION engine/flywheel system on the urban cycle provides energy savings over a broad set of design operating range values. However, for a short range design it cannot achieve as much energy savings as the battery system.

It should be noted that, if a conventionally powered car were equipped with a continuously variable transmission of the type used in the hybrid system, the engine in the conventional vehicle could be also expected to operate at improved efficiency. This consideration would appear to diminish or possibly eliminate the relative energy consumption superiority of the hybrid heat engine/flywheel vehicle. However, the hybrid vehicle, with its energy storage system, can benefit further from the energy-saving potential of regenerative braking -- an operational consideration not present with the conventionally powered vehicle. Hence, in comparing the best possible systems, the ability to recover energy through regenerative braking must be considered as the fundamental gain possible with the heat engine/ flywheel hybrid system for operation in urban driving situations.

S.5.1.5 Energy Savings Potential of Super Flywheel Systems

A brief examination was made of the type of performance that might be expected from an advanced design, high-speed, plastic-reinforced composite (Kevlar) flywheel. The intention was to provide greater energy storage capability than was available with the steel rotor and thereby improve the vehicle operating range whenever the onboard heat engine was not providing full recharge energy to the flywheel ($\gamma < 1.0$).

It was assumed for purposes of rotor sizing that a guard ring was not required, thereby allowing a maximum possible rotor diameter within the vacuum housing mounted in the hybrid vehicle. The resulting design was a 2-foot-diameter Kevlar rotor operating at 42,000 rpm.

An initial evaluation showed that the flywheel resulted in totally unacceptable performance because of excessive parasitic losses related to aerodynamic, bearing, and seal drag, and vacuum pump power requirements. Hence, a large amount of engine power was required to keep the wheel recharged, and this resulted in energy consumption much higher than that for a conventionally powered car.

Attempting to lower the pressure in the flywheel housing to reduce windage losses only caused a large increase in pump power requirements. Therefore, in an effort to relieve this problem, it was assumed that improved seals could be developed to hold pressures in the rotor housing down to 10^{-3} mmHg without requiring an increase in pump power requirements over those needed to sustain 5 mmHg pressure. Even this liberal assumption did not produce results equivalent to those for the case of a steel rotor as seen in Figure S-47, where the relative energy consumption is plotted as a function of range for a 4000-lb series configuration hybrid car operating over the EPA Urban Driving Cycle. Energy savings in all fuels are possible only below about 25 miles and in petroleum-based fuels below about 50 miles. The minimum design range did improve slightly -- from about 7.5 miles for the steel wheel to 17.5 miles for the Kevlar wheel.

Therefore, high-speed plastic-reinforced wheels do not appear to be a viable system for the heat engine/flywheel hybrid vehicle, unless parasitic losses can be reduced to much lower levels. This is desirable, even if the flywheel energy storage capacity is diminished, because the importance of capacity is related only to how many repetitive peak accelerations of the vehicle are to be designed into the system. The heat engine will always continue to resupply energy to the flywheel at most all other times in urban-type driving.

S.5.2 ENERGY CONSUMPTION CHARACTERISTICS FOR THE EPA HIGHWAY DRIVING CYCLE

Analysis results for series and parallel configurations in three vehicle weights are presented in Figures S-48, S-49, and S-50. In all cases, the γ range is very small and, as explained in Section S.5.1.1, is due to all of the heat engine power flowing through the flywheel to the vehicle drive wheels. As before, unless the vehicle is operated at values very close to $\gamma = 1.0$, the possible design operating range will be too small to be feasible, particularly on this driving cycle. Hence, the discussion will be confined to the case of $\gamma = 1.0$.

In Figure S-48a, fuel consumption for the 4000-lb series configuration car exceeds that for the conventionally powered car by about

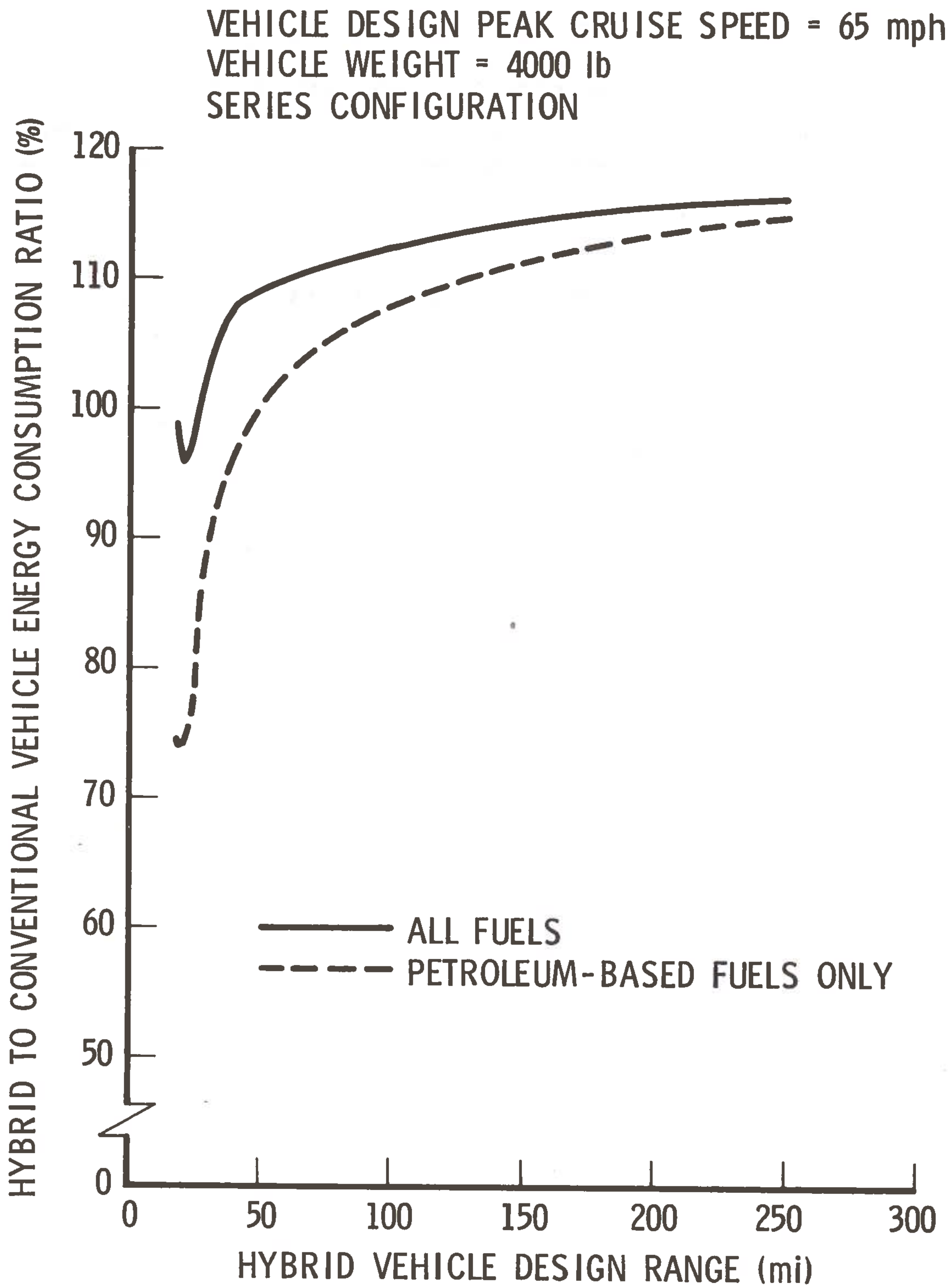
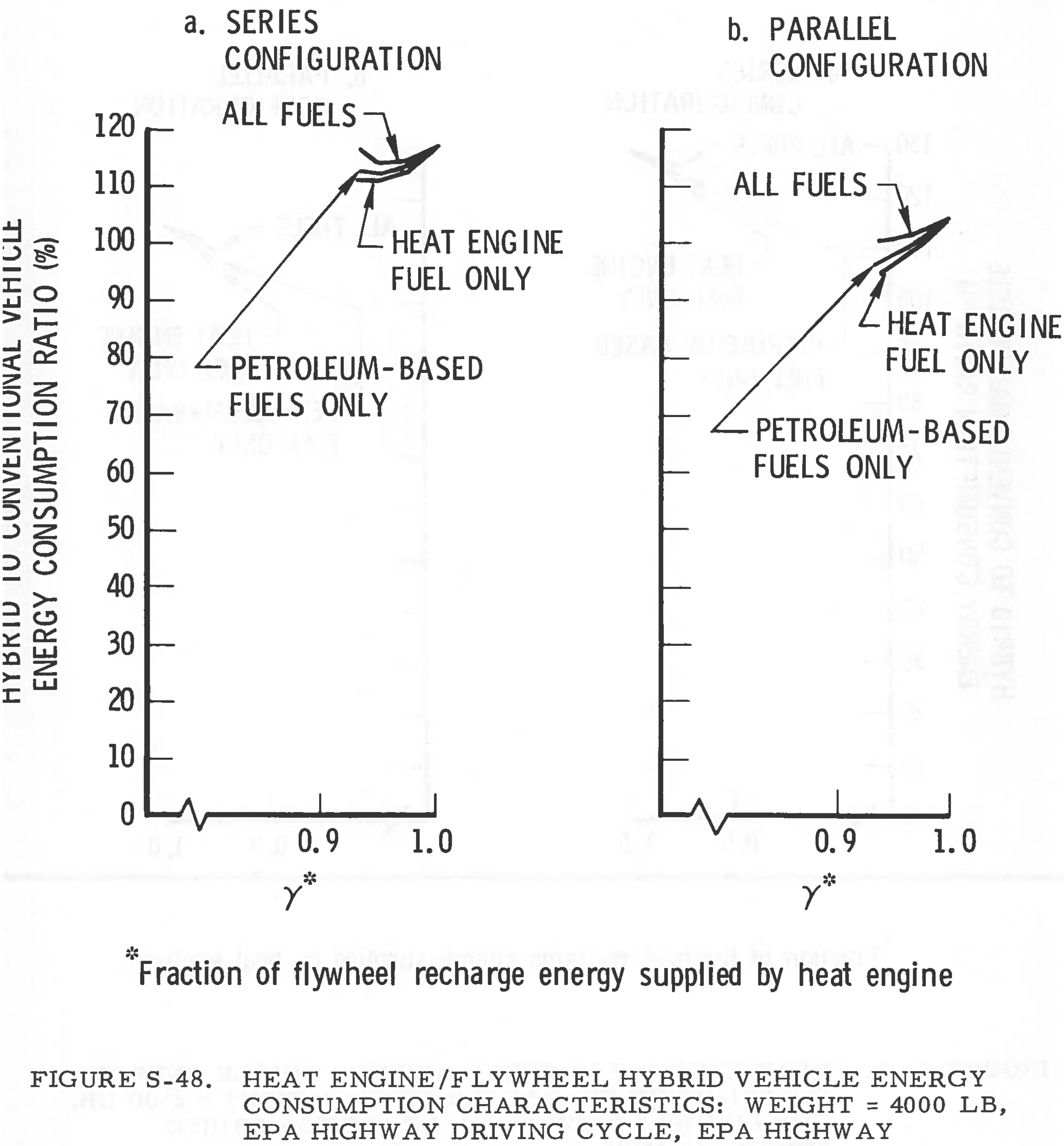
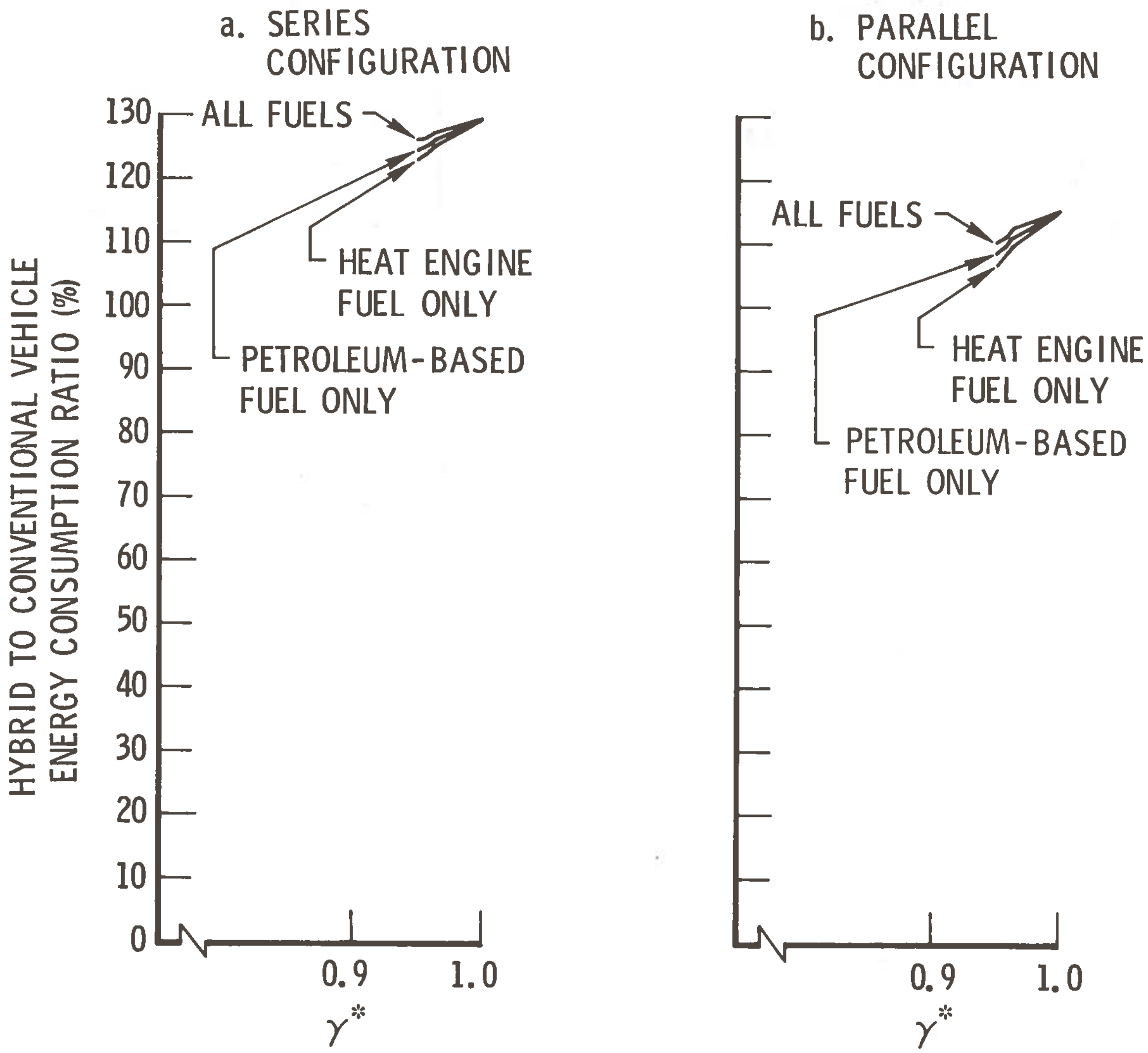


FIGURE S-47. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, 2.0-FT-DIAMETER HIGH-SPEED PLASTIC COMPOSITE ROTOR



*Fraction of flywheel recharge energy supplied by heat engine

FIGURE S-48. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, EPA HIGHWAY DRIVING CYCLE, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of flywheel recharge energy supplied by heat engine

FIGURE S-49. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

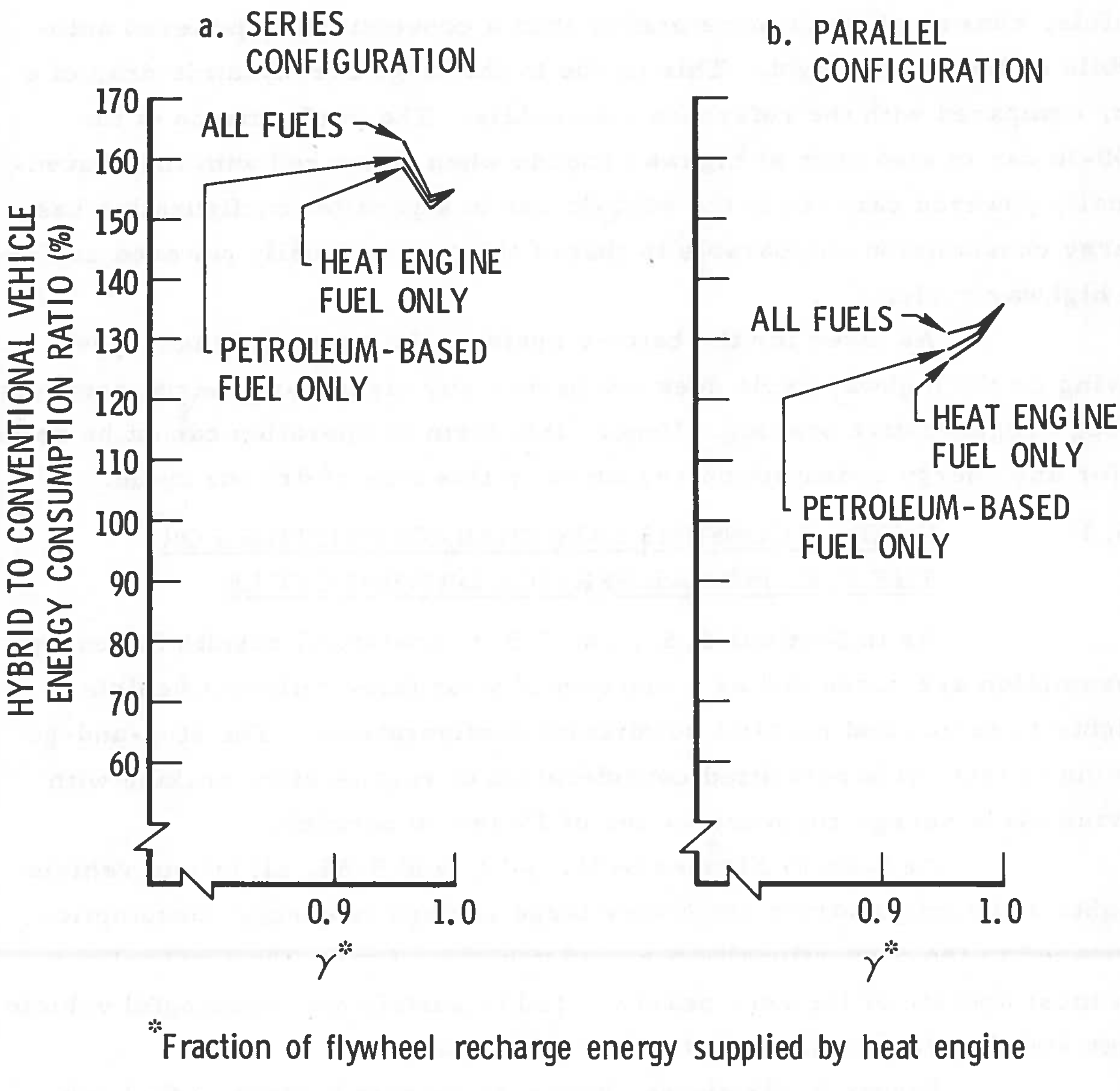


FIGURE S-50. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

16 percent. The parallel configuration (Figure S-48b) uses energy more efficiently and shows an excess fuel consumption of only about 4.5 percent. Equivalent results for the 2500-lb car are 129 and 115.5 percent (Figure S-49). Similarly, for the 6000-lb van (Figure S-50), the results are 155 and 136 percent -- a significantly greater energy consumer.

These results show that the 6000-lb hybrid van, as a highway vehicle, consumed much more energy than a conventionally powered automobile of the same weight. This is due to the large aerodynamic drag of a van, compared with the reference automobile. The performance of the 2500-lb car is also poor at highway speeds when compared with the conventionally powered car. Only the 4000-lb car in a parallel configuration has energy consumption comparable to that of the conventionally powered car on the highway cycle.

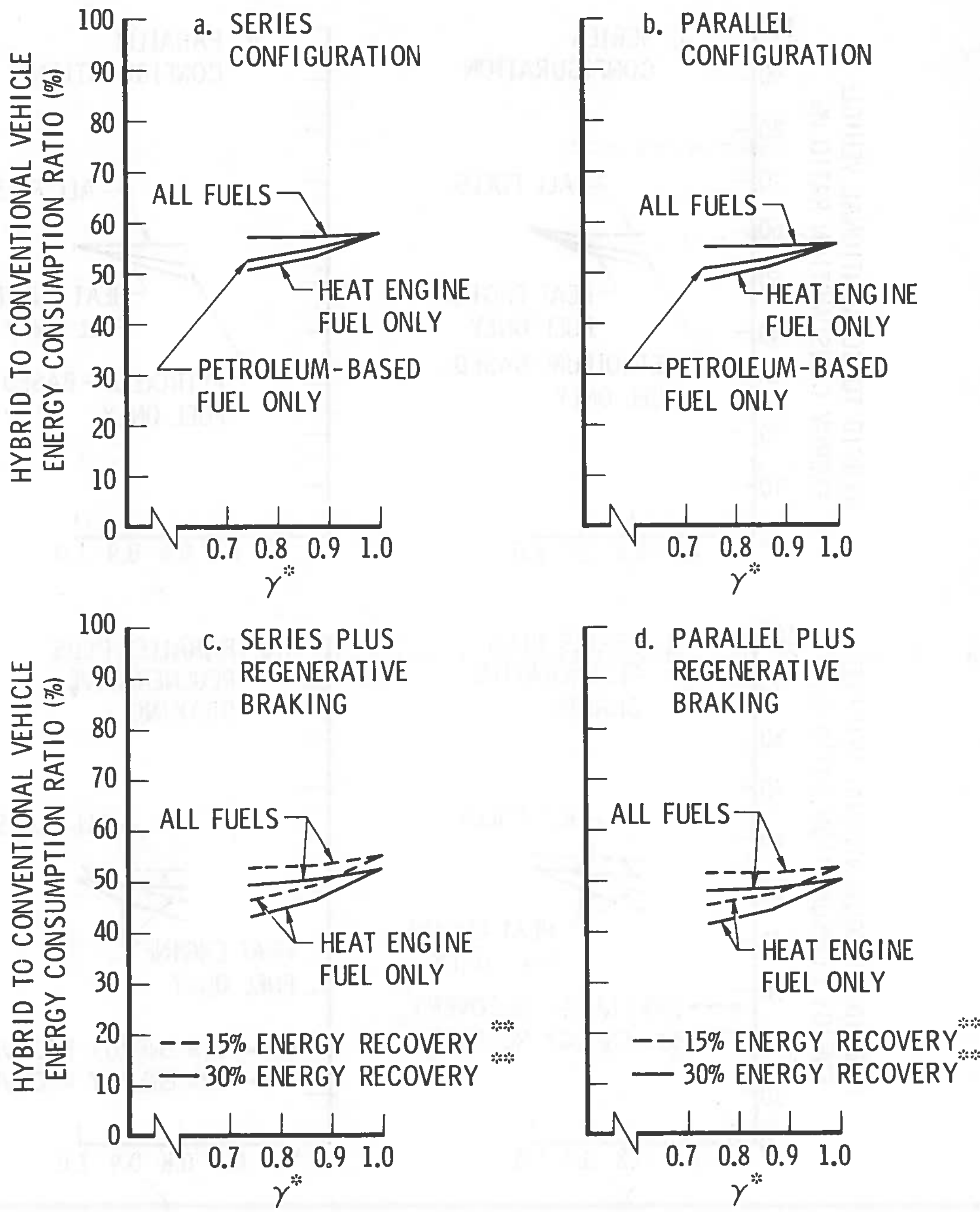
As noted for the battery system, the sustained high-speed driving on the highway cycle does not permit any significant energy recovery through regenerative braking. Hence, this form of operation cannot be relied on for any energy consumption reduction on this type of driving cycle.

S.5.3 ENERGY CONSUMPTION CHARACTERISTICS FOR THE U.S. POSTAL SERVICE DRIVING CYCLE

As in Sections S.5.1 and S.5.2, analytical results for energy consumption are presented as a function of γ for three different vehicle weights in series and parallel powertrain configurations. The stop-and-go driving of this cycle permitted consideration of regenerative braking with driving cycle energy recovery values of 15 and 30 percent.

As seen in Figures S-51, S-52, and S-53, all hybrid vehicle weights and configurations show very large savings in energy consumption compared to the conventionally powered vehicle. Again, the flywheel system must operate at (or very near) $\gamma = 1.0$ to sustain any meaningful vehicle range and the discussion is confined to this value.

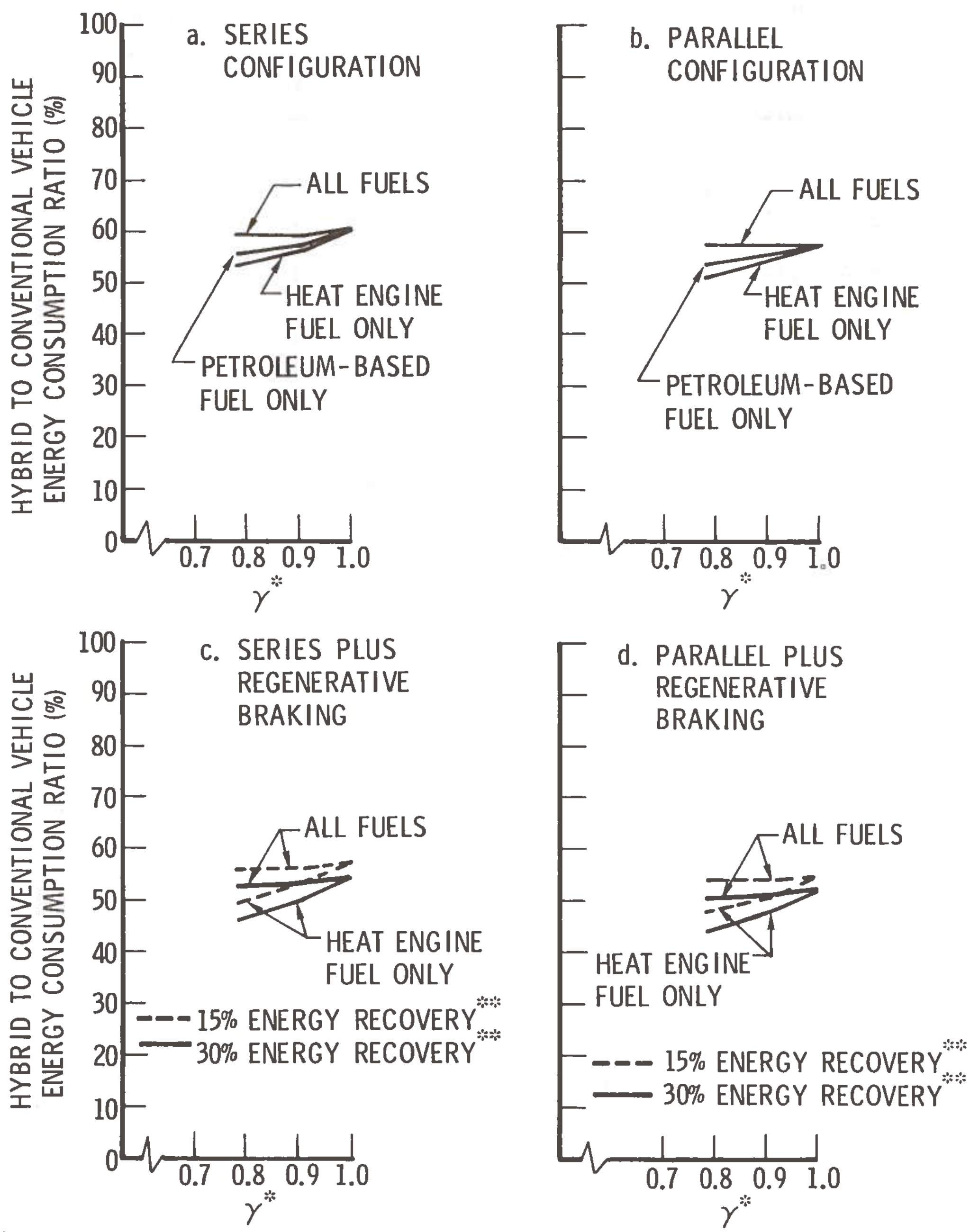
Figure S-51a shows about a 42 percent savings in fuel consumption for the 4000-lb series configuration. The greatest fuel savings are offered by the parallel configuration, which shows a 50 percent savings when 30 percent of drive wheel energy is recovered. Similar results for a



*Fraction of flywheel recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in flywheel

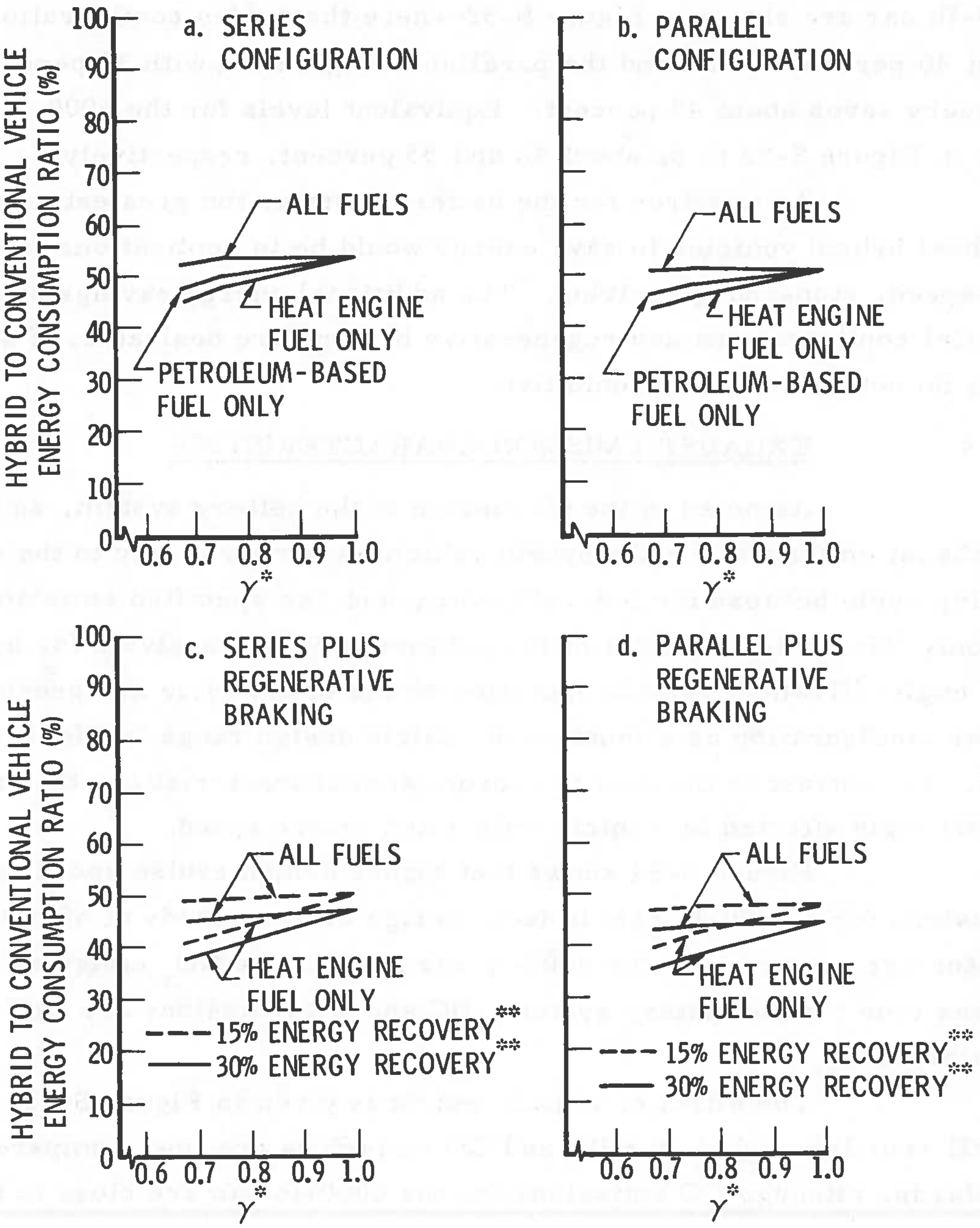
FIGURE S-51. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of flywheel recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in flywheel

FIGURE S-52. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of flywheel recharge energy supplied by heat engine, or by heat engine plus regenerative braking

**Percent of total driving cycle energy recovered and stored in flywheel

FIGURE S-53. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

2500-lb car are shown in Figure S-52 where the series configuration saves about 40 percent in fuel and the parallel configuration with 30 percent energy recovery saves about 48 percent. Equivalent levels for the 6000-lb van are seen in Figure S-53 to be about 46 and 55 percent, respectively.

As was true for the battery system, the greatest potential for flywheel hybrid vehicles to save energy would be in applications involving low-speed, stop-and-go driving. The additional energy savings offered by parallel configurations and regenerative braking are desirable, if system costs do not prove to be prohibitive.

S. 5. 4 EXHAUST EMISSION CHARACTERISTICS

As noted in the discussion of the battery system, an evaluation of exhaust emissions for the hybrid vehicle is pertinent only to the urban driving cycle because the federal government has specified emission standards for only this cycle. Results of the exhaust emission analysis for hybrid heat engine/flywheel vehicle operation on the urban cycle are presented for a series configuration as a function of vehicle design range in Figures S-54 and S-55. In contrast to the energy consumption characteristics, the emissions are strongly affected by vehicle weight and cruise speed.

Figure S-54 shows that higher design cruise speeds give lower emissions for a 4000-lb car; in fact, design cruise speeds of 65 mph or greater are required for the 4000-lb car to meet the NO_x emission standard. As was true for the battery system, HC and CO emissions are well below the standard.

The effect of vehicle weight is given in Figure S-55. Again, for all vehicle weights, the HC and CO emissions are low, compared with the standards, although CO emissions for the 6000-lb van are close to the maximum permissible value. The van also has NO_x emissions well in excess of the standards, and the 4000-lb car is marginally acceptable. Although not illustrated, analysis shows that the use of regenerative braking or the modification to a parallel configuration on the 4000-lb car can reduce the NO_x emissions well below the standard, even at the higher vehicle range. Such alternatives are still insufficient to permit the 6000-lb van to meet the NO_x standard. Therefore, for the urban cycle, it is estimated that the

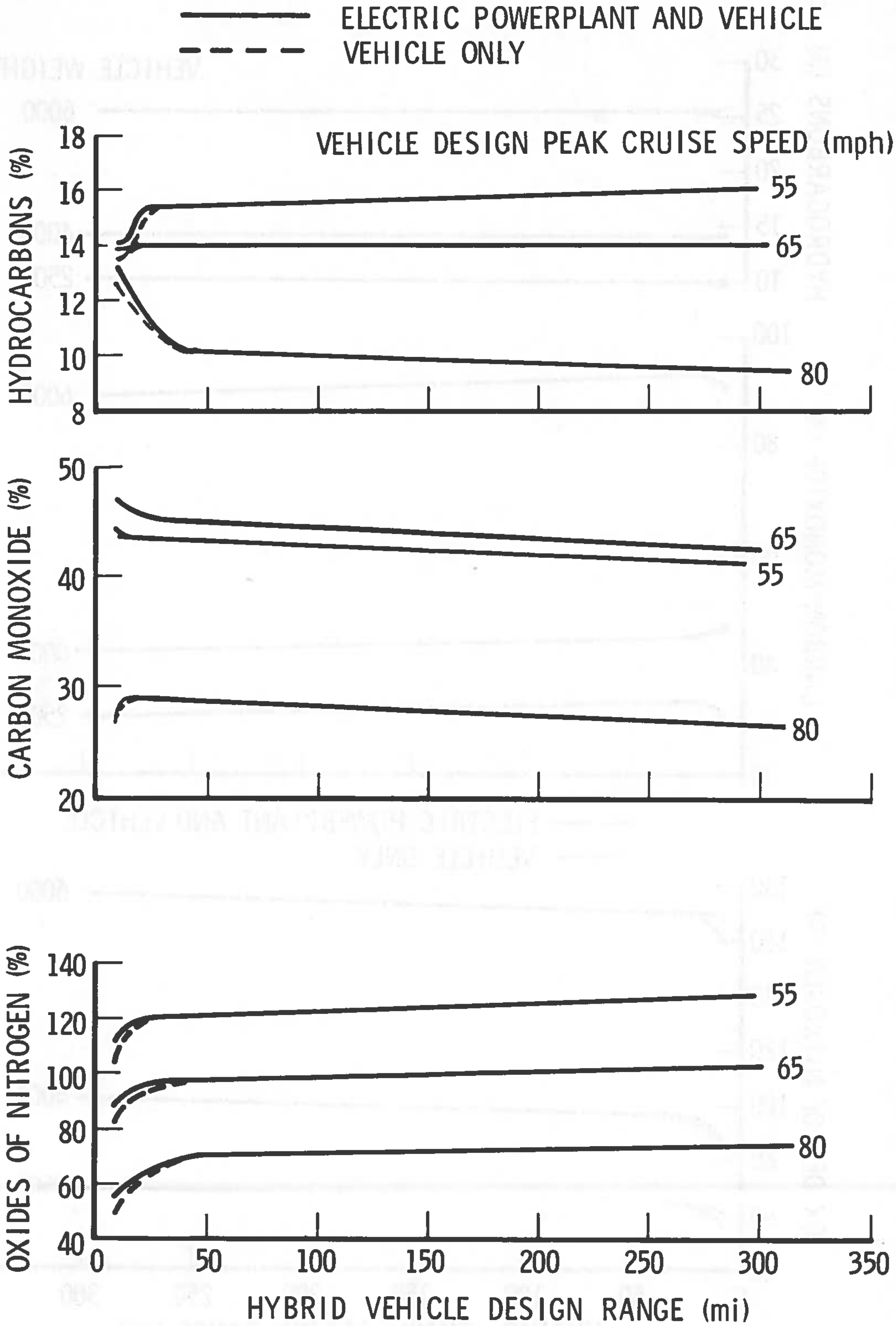


FIGURE S-54. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE WEIGHT = 4000 LB, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

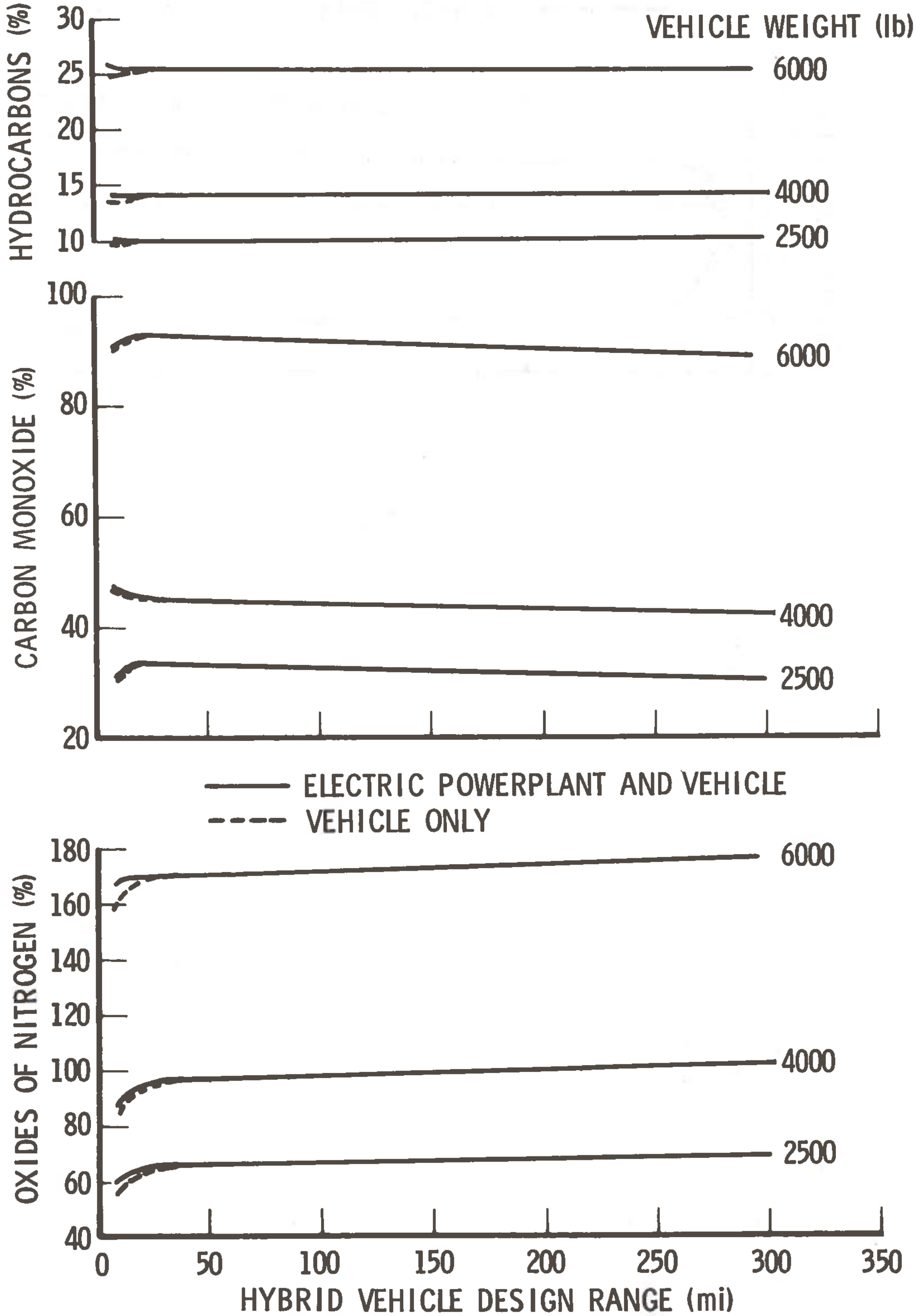


FIGURE S-55. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS) hybrid heat engine/flywheel van will exceed the NO_x standard unless a concentrated effort at revising design cruise speeds, design acceleration, and powertrain component operation could result in major reductions in NO_x emissions.