

HYBRID VEHICLE TECHNOLOGY CONSTRAINTS AND APPLICATION ASSESSMENT STUDY

Volume IV: Sections 10, 11, and Appendix

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The Aerospace Corporation
Environment and Energy Conservation Division
El Segundo CA 90245



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FINAL REPORT

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16. Abstract This four-volume report presents analyses and assessments of both heat engine/battery- and heat engine/flywheel-powered hybrid vehicles to determine if they could contribute to near-term (1980-1990) reductions in transportation energy consumption under several sets of operational conditions: urban driving, highway driving, and stop-start, low-speed delivery service conditions. In addition, the impact of such hybrid vehicle use on vehicle-related exhaust emissions is determined, and the ability to accommodate a different energy resource base in the longer term is evaluated; i.e., by permitting a portion of the recharge energy for the on-board energy storage device (battery or flywheel) to be provided by wall-plug electric power from the utility industry instead of from the on-board heat engine. Alternative paths for power transmission from the heat engine to the vehicle drive wheels are considered along with the potential of regenerative braking to reduce vehicle energy consumption. This last of four volumes is concerned with the hybrid vehicle's energy consumption and exhaust emissions. Section 10 discusses factors such as vehicle weight, peak cruise speed, and regenerative braking. Section 11 details technological constraints to introduction of the hybrid vehicle and identifies applications that could benefit most from its energy conservation potential.			
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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
ft
yd
mi

centimeters
meters
kilometers

cm
m
km

AREA

in²
ft²
yd²
mi²

square inches
square feet
square yards
square miles
acres

cm²
m²
km²
ha

MASS (weight)

oz
lb

grams
kilograms
tonnes

g
kg
t

VOLUME

tsp
Tbsp
fl oz
c
pt
qt
gal
ft³
yd³

milliliters
milliliters
milliliters
liters
liters
liters
cubic meters
cubic meters

ml
ml
ml
l
l
l
m³
m³

TEMPERATURE (exact)

°F Fahrenheit temperature

5/9 (after subtracting 32)

Celsius temperature

°C

Approximate Conversions from Metric Measures

When You Know Multiply by To Find Symbol

LENGTH

millimeters
centimeters
meters
kilometers

inches
feet
yards
miles

in
ft
yd
mi

AREA

square centimeters
square meters
square kilometers
hectares (10,000 m²)

square inches
square yards
square miles
acres

in²
yd²
mi²

MASS (weight)

grams
kilograms
tonnes (1000 kg)

ounces
pounds
short tons

oz
lb

VOLUME

milliliters
liters
liters
cubic meters
cubic meters

fluid ounces
pints
quarts
gallons
cubic feet
cubic yards

fl oz
pt
qt
gal
ft³
yd³

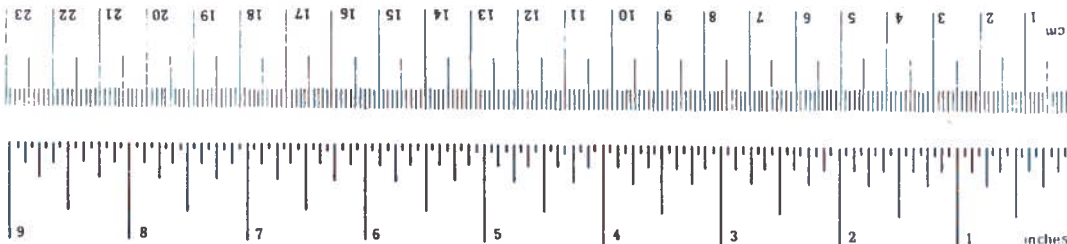
TEMPERATURE (exact)

°C Celsius temperature

9/5 (then add 32)

Fahrenheit temperature

°F



* 1 in = 2.54 centimeters. For a more exact conversion, use 1 in = 2.54 centimeters. Units of Length and Measure, Page 32, 25, 50 (Copyright © 1994 by The McGraw-Hill Companies, Inc.)

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10. ENERGY CONSUMPTION AND EXHAUST EMISSIONS OF HYBRID VEHICLES

Analyses were conducted for both heat engine/battery-powered and heat engine/flywheel-powered hybrid vehicles to determine their energy consumption under several sets of operational conditions: urban driving; highway driving; and stop-start, low-speed delivery service conditions. In addition, the impact of such hybrid vehicle usage on vehicle-related exhaust emissions was determined.

Three vehicles were evaluated in the study: 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: hydrocarbons (HC) = 1.5 gm/mi, carbon monoxide (CO) = 15.0 gm/mi, and oxides of nitrogen (NO_x) = 3.1 gm/mi. The term "vehicle-related" refers to the sum of energy (or of emissions) from the vehicle and from the electric generating plant that is used to supply power for recharging the hybrid vehicle energy storage device. Therefore, the fuel consumption and emission characteristics of the generating plant were simulated along with those of the vehicle.

Hybrid vehicle operation was simulated by use of the computer program discussed in Section 8 and by use of the performance characteristics described in Section 5 for powertrain components, in Section 6 for stationary electric generating plants, and in Section 7 for hybrid and conventionally powered (baseline) vehicles. The sizing analysis described in Section 9 was instrumental in specifying the rated power of the heat engine and the gear ratios required in the powertrain.

The hybrid powertrain examined in greatest detail was series in configuration. It was operated over the EPA Urban Driving Cycle with the vehicle simulation computer program. Analytical results were also obtained for powertrain operation over the EPA Highway Driving Cycle and the U.S. Postal Service Driving Cycle.

For each of these driving cycles, the effects of a parallel configuration and of regenerative braking were determined separately, as described in Section 8. If engine specific fuel consumption and specific emissions remain unchanged, use of a parallel configuration could be expected to offer reductions in vehicle energy consumption and emissions from the series configuration because of the improved powertrain efficiency brought about by the additional link of the heat engine to the vehicle drive wheels via a single transmission.

The ability to recover kinetic energy by regenerative braking during vehicle deceleration, to store the energy, and then to reuse it for vehicle propulsion has the potential for offering significant reductions in vehicle energy consumption. Of major importance for a given weight vehicle is the manner in which vehicle deceleration occurs and the efficiency for energy conversion in the vehicle powertrain. Vehicle deceleration, of course, varies with driver habits, type of roadway, and type of traffic. Therefore, regenerative braking was treated parametrically. Based on the discussion presented in Section 3.3, 10 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.

In the subsequent discussion, the driving cycle characteristics are described, the powertrain component operation is depicted, and the vehicle-related energy consumption and exhaust emissions are summarized for select combinations of vehicle design peak cruise speed, peak acceleration, and weight. The effects of discrete variations in component efficiency and powertrain gear ratios for the series configuration are also covered. (A matrix showing the parametric variations included in the analysis is given in Tables 10-1 and 10-2.)

In the presentation of results, hybrid vehicle-related energy consumption is given as a percentage of conventionally powered vehicle energy consumption. The hybrid vehicle-related exhaust emissions are

expressed as a percentage of the 1975-76 federal emission standards and are shown only for the EPA Urban Driving Cycle. 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; therefore, no such discussion is included.

10.1 ENERGY CONSUMPTION AND EXHAUST EMISSIONS FOR HEAT ENGINE/BATTERY HYBRID VEHICLES

Hybrid vehicle characteristics are presented as a function of time for a 4000-lb series configuration car with a design cruise speed of 65 mph and a nickel-zinc energy storage battery system. Other cruise speeds, vehicle weights, and powertrain configurations are discussed in regard to the integrated results that summarize vehicle-related energy consumption and exhaust emissions.

10.1.1 Analysis for EPA Urban Driving Cycle

10.1.1.1 Cycle and Vehicle Propulsion Characteristics

The EPA Urban Driving Cycle encompasses a wide variety of vehicle speeds, accelerations, and decelerations over a period of 1372 seconds, covering a distance of 7.45 miles with an average speed of 19.55 mph. The velocity history is shown in Figure 10-1; vehicle speeds range as high as 56.7 mph. Figure 10-2 shows the vehicle acceleration/deceleration time profile; decelerations and accelerations reach about the same peak value of 3.3 mph/second. Distance traveled by the vehicle as a function of time is given in Figure 10-3. The wheel power required for propelling a 4000-lb vehicle is given in Figure 10-4. Peaking at about 54 hp, this power is necessary to overcome vehicle road load as well as to accelerate the vehicle mass.

10.1.1.2 Powertrain Component Characteristics

Component characteristics for a series configuration are presented as a function of time throughout the driving cycle for two different fixed minimum power settings of the heat engine/generator (see Section 2.3). When the minimum power for propulsion is set at zero ($\tau = 0$)*, the heat

* τ = fixed minimum power setting of generator expressed as a fraction of rated power

engine/generator is not capable of providing any recharging energy to the battery; all recharging then comes from an electrical wall outlet. Engine speed and power output for vehicle propulsion, as shown in Figures 10-5 and 10-6, are then required to follow wide excursions from the minimum power setting in order to provide road-load power for the vehicle. The speed of the engine is that necessary to provide the brake horsepower output which includes not only the propulsion power shown in Figure 10-6, but also the vehicle accessory/engine auxiliary load given in Figure 10-7. Hence, at 4339 rpm, the peak power out of the engine for this illustration is 43.9 hp, of which 38.3 hp is for propulsion and 5.6 hp for accessories/auxiliaries.

By contrast, at the higher fixed minimum power settings, the engine speed and power variations are limited to the high-speed portion of the driving cycle between 200 and 300 seconds. This is seen in Figures 10-8, 10-9, and 10-10 for engine speed, engine power for propulsion, and vehicle accessory/engine auxiliary power demand, respectively. The power setting used for illustration in this case ($\tau = 0.30$) does provide battery recharge power and is large enough to completely recharge the battery at the end of the driving cycle without the need for recharge power from an electrical wall outlet (in fact, slightly in excess of the power needed for complete recharge). The virtual independence of engine operation from wheel power requirements, in this case, provides an illustration of how hybrid vehicle heat engines and emission control systems design requirements can be markedly different from those for conventionally powered vehicles.

The next two illustrations, Figures 10-11 and 10-12, show the energy provided at the engine shaft for all vehicle power requirements as a function of time. When all battery recharging is accomplished with the heat engine ($\tau = 0.3$), there is about a factor of 3 increase in vehicle onboard energy compared to the requirements when there is total reliance on wall charging ($\tau = 0$).

Battery characteristics are illustrated in Figures 10-13 through 10-19. The battery effective discharge current* passing to the electric

*The actual discharge current is considerably higher and lasts for only a fraction of a second because of the "chopped" power. This value is an "average" current, lasting for 1 second, and properly accounts for power and energy leaving the battery.

drive motor for vehicle acceleration power is shown in Figure 10-13 for $\tau = 0$. A peak value of about 415 amp is required for a system voltage of about 110 volts. (A higher system voltage would possibly be chosen for a finalized design to improve the overall powertrain efficiency.) In Figure 10-14, a peak value of 390 amp is seen for the case of $\tau = 0.3$. In fact, most of the discharge current values have been reduced from the case of $\tau = 0$. This reduction in battery discharge current is brought about by the increase in current available from the engine/generator as the fixed minimum power level is increased. As discussed in Section 2, at the lower vehicle speeds, the engine/generator does provide a portion of the vehicle acceleration power requirements.

Battery charging current is shown in Figure 10-15 for $\tau = 0.3$ (charging current is zero for $\tau = 0$). The charging current is limited to a maximum value of about 50 amp in this case. This limit on charging current is a function of the battery state of charge, battery capacity, limiting maximum battery cell voltage, and limiting charging capability of the generator. For this illustration, the peak current is set by the generator. This is generally the case; therefore, energy is wasted only when the battery is close to, or at 100 percent state of charge.

The resulting battery state of charge is shown as a function of time in Figures 10-16 and 10-17 for τ values of zero and 0.3, respectively. In the former case, almost 10 percent of the battery capacity has been expended by the end of the driving cycle, while in the latter case the battery charge has been fully restored. The accompanying cell voltage histories are given in Figures 10-18 and 10-19; there is little variation from the nominal value of 1.815 volts.

Because the heat engine is run continuously, battery charging current from the generator is available even when the battery is fully charged. This power must be discharged to a passive load and constitutes wasted energy. An accounting of the wasted energy at the heat engine output shaft is given in Figure 10-20 for $\tau = 0.30$. As noted previously, at this engine/generator setting, the energy generated is slightly more than required to fully recharge the battery, and rapid increases in wasted energy are encountered. The final

value of almost 0.36 kW-hr is about 7 percent of the total energy expended by the heat engine. (If the battery had an initial state of charge significantly less than 100 percent, the wasted energy could be decreased almost to zero.)

Electric drive motor characteristics are presented in Figures 10-21 through 10-25; they are independent of the generator τ setting. The motor speed history is shown in Figure 10-21. It follows the vehicle speed characteristics given in Figure 10-1 and peaks close to 10,000 rpm at 240 seconds. In Figure 10-22, the motor power output history is shown. It follows the vehicle drive wheel power characteristics shown in Figure 10-4 and differs only by the intervening efficiencies of the gear train and differential; a peak value of about 56 hp is required at close to 200 seconds. The accompanying motor current and voltage histories are given in Figures 10-23 and 10-24, respectively. Peak motor currents close to 720 amp occur primarily at conditions of high vehicle acceleration at fairly low vehicle speeds. Motor voltage peaks at about 80 volts and is generally highest at the higher vehicle speeds. Finally, motor efficiency is shown as a function of time in Figure 10-25. Values generally range from about 70 to 85 percent, averaging near 78 percent. (Values of 100 percent are anomalies of the computer program occurring only when the vehicle is stationary.) The very low values of efficiency (as low as 1 to 2 percent) occur when the vehicle is accelerating from a stop -- significant power levels are being delivered to the motor but it is producing a very small power output due to the low rpm.

10.1.1.3 Example of Analysis Results

The previous discussion covered powertrain characteristics at the lowest and highest values of the generator fixed minimum power setting, τ , to illustrate the variations to be expected as the vehicle negotiates the driving cycle. By varying τ between the low and high values, trends in the critical parameters defining vehicle energy consumption can be observed. Examples of these parameters are heat engine power output, engine fuel energy expended, and engine energy wasted.

At each value of τ , the heat engine provides a certain amount of energy for recharging the battery, as determined at the end of the driving cycle. Hence, an appropriate independent parameter for plotting summary

curves of vehicle energy expenditure is a term designated gamma (γ). The parameter γ is the fraction of battery recharge energy that is provided by the onboard heat engine (or heat engine plus regenerative braking). When γ equals zero, all recharging is accomplished by power from an electric wall outlet;* when γ equals 1.0, all recharging is accomplished by power from the engine on board the vehicle. Intermediate values allow the recharging to be divided between these two energy sources. Some examples of heat engine characteristics related to energy expenditures are given as a function of γ for the series configuration powertrain.

An indication of the variation with γ of the heat engine power available for propulsion is given in Figure 10-26. Values range from zero horsepower at γ of zero to 14.25 hp at γ of 1.0.

The specific engine operation constraints with respect to horsepower and rpm, as discussed in Section 5, resulted in brake specific fuel consumption (BSFC) values generally ranging from 0.55 to 0.60. (Minimum BSFC for the selected engine was 0.5.) For fuel with an assumed energy release content of 18,600 Btu/lb fuel, the engine efficiency ranged from about 23 to 25 percent. The energy expended over the driving cycle by the heat engine fuel is plotted in Figure 10-27 as a function of γ . At γ of zero, the 10.7 kW-hr of energy expended was used for providing power to overcome vehicle road load and vehicle accessory/engine auxiliary loads; no energy was expended for battery recharging. At γ of 1.0, the 21.5 kW-hr of energy expended was used for the loads just noted plus the power needed to fully recharge the battery.

As noted in Section 10.1.1.2, whenever the battery was fully charged or whenever the generator charging current exceeded the battery acceptance rate, the excess power was dissipated in a passive load. This wasted energy, as determined at the engine shaft output, is plotted versus γ in Figure 10-28. Wasted energy is generally less than 2 percent of the energy provided by the heat engine, but engine operation in excess of that needed to fully recharge the battery can increase losses to 7 to 10 percent.

*Energy supplied by stationary electric generating plant

At the end of the driving cycle, the energy contained in all forms of fuel consumption was determined. The fuel energy consumed was categorized as follows: (a) heat engine fuel only, (b) heat engine plus electric generating plant petroleum-based fuels, (c) heat engine plus all electric generating plant fuels. The results for a series configuration powertrain are expressed as a percentage of the fuel energy expenditure for conventionally powered cars (see Section 7), and plotted versus γ in Figure 10-29. At $\gamma = 0$, when the electric generating plant provides all battery recharging, the vehicle heat engine (fueled with gasoline) uses only 60 percent of the fuel energy of a conventionally powered car. This energy factor rises to about 71 percent when petroleum-based fuels used at the electric generating station are included. Accounting for energy from all fuels at the electric generating station increases this figure to about 91 percent. The leveling out of the heat engine energy consumption curve below $\gamma = 0.1$ 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 at the higher power setting for $\gamma = 0.1$.

As γ increases and the heat engine provides more of the battery recharge energy, the energy ratios for each source category tend to merge and continue to increase until energy expended is greater than for a conventionally powered car. These trends are indicative of (a) the improved energy conversion efficiency of electric generating plants (including power transmission to an electric wall outlet) when contrasted with automotive internal combustion gasoline engines; and (b) the poorer overall powertrain efficiency of a series configuration heat engine/battery hybrid car when contrasted with a conventional car. However, subject to the assumptions used in this analysis, the results do show that there are operating regimes for this particular hybrid vehicle whereby significant savings in petroleum-based fuels or in all types of fuels can be achieved.

10.1.1.4 Summary of Hybrid Vehicle Energy Consumption Characteristics

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, impact of regional characteristics of electric generating plants, and sensitivity of results to changes in powertrain component characteristics.

10.1.1.4.1 4000-lb Car

Figure 10-30 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 operating over the same cycle (at 14.2 mpg or 2.38 kW-hr/mi, as given in Section 7).

10.1.1.4.1.1 Series Configuration

As shown in Figure 10-30a, 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 and more wall-plug electricity 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 utility power plant) is approximately 90 percent that of the reference baseline vehicle, or approximately a 10 percent savings in total fuel energy consumption. As noted previously, 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 at the higher power setting for $\gamma = 0.1$. (This same characteristic can be seen in subsequent illustrations for the 2500- and 6000-lb vehicles.)

In order to use less heat engine fuel (gasoline) than the baseline comparison vehicle, the hybrid vehicle would have to use heat engine fixed minimum power settings which 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), less than 55 percent of the battery

recharge energy would be provided by the heat engine ($\gamma \leq 0.55$) in order to use less energy than the baseline vehicle. To save on total energy (gasoline plus all fuels at the electric generating power plant), less than 44 percent of the battery recharge energy would be provided by the heat engine.

It is of interest to note that, 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 curves designated "heat engine fuel only," this trend is certainly expected (barring marked changes in engine efficiency). For the other curves designated as "petroleum-based fuels only" and "all fuels," this trend is due to the fact that, even under hybrid operating conditions, the onboard heat engine efficiency is less than the combined efficiencies of stationary 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 wall-plug power for battery recharge energy, less total fuel energy is consumed per vehicle mile traveled.

10.1.1.4.1.2 Parallel Configuration

As shown in Figure 10-30b, 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 and more wall-plug recharge energy is used (as γ becomes smaller).

10.1.1.4.1.3 Regenerative Braking Effects

Figures 10-30c and 10-30d 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

*Percent of total driving cycle energy recovered and stored in battery by regenerative braking system

save gasoline, and at γ values below 0.8 to conserve total energy. With 10 percent energy recovery, these γ values become 0.8 and 0.6, respectively.

In the case of the parallel configuration, significant gasoline and total energy savings are accomplished at all γ values with either 10 or 15 percent energy recovery (with increased savings as γ is reduced).

10.1.1.4.2 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 10-31. Here, the basis of comparison is the gasoline energy consumption of the 2500-lb vehicle given in Section 7 (21.7 mpg or 1.56 kW-hr/mi). As can be noted, the basic effects of configuration (series versus parallel) and of regenerative braking are similar to those described for the 4000-lb car.

10.1.1.4.3 6000-lb Van

Figure 10-32 depicts the energy consumption characteristics of the 6000-lb hybrid vehicle, as compared with the gasoline energy consumption of the baseline vehicle given in Section 7 (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- and 2500-lb hybrid vehicles.

10.1.1.4.4 Range Implications

The preceding plots of energy expenditure versus 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 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, this form of operation requires the vehicle to be recharged from an electric wall outlet for a number of 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 value of γ used in the design of a hybrid vehicle, and it is of interest

to view energy expenditures when plotted versus 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 consumption of fuel and size of fuel tank, and (b) rate of depletion of stored battery energy and size of batteries. An example of the range variation with γ for each of the aforementioned considerations is shown in Figure 10-33.

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 10-33 by the curve on the left designated "range based on battery energy."

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

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 versus range, curves similar to those shown in Figure 10-33 were used in conjunction with curves like those shown in Figures 10-30 through 10-32. 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 10-33), a criterion for selection was necessary. This was readily resolved by observing that energy consumption always showed an increase with γ . Therefore, the lower value of γ was selected in order to have the system operate at the lesser of the two possible values for energy consumption. This means that for the vehicle energy consumption versus design range curves to be presented, the battery is always range-controlling.

10.1.1.4.5 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 10-34 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 range less than about 105 and 115 miles, respectively. When considering saving just petroleum-based fuels for these reduced-speed vehicles, comparable range values are 200 and 155 miles, respectively. At the lowest range shown of about 60 miles, these hybrid vehicles consume in all fuels about 85 to 90 percent of the energy of conventionally powered vehicles, and only about 65 to 70 percent in petroleum-based fuels. 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 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 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, component weights in the powertrain must increase accordingly. As shown in Section 9, the weight available for batteries then decreases and the required specific power (W/lb) of the battery rises sharply. Reduction in available battery weight would likewise reduce the available ampere-hour capacity and 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 more energy to be wasted during battery recharge.

To illustrate the effect of vehicle weight, a set of energy consumption curves is shown in Figure 10-35 for a constant design peak cruise speed of 65 mph for three different series configuration vehicle weights: 2500, 4000, and 6000 pounds. The lowest energy consumption and greatest possible design operating range is found with the 4000-lb car which, as had been shown in Figure 10-34, has energy savings at design operating ranges less than 115 miles for all fuels and at ranges 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 10-35. 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 10-35 would have shown a definite trend of decreasing relative energy consumption with increasing vehicle weight.

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 10-36 through 10-38 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 both 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, seen for the 4000-lb car with 15 percent energy recovery.

Still greater energy savings are possible with the parallel configuration, as seen in Figures 10-39 through 10-41. 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 type of urban driving that is characterized by the EPA Urban Driving Cycle. Regenerative braking is decidedly of significant value in conserving energy. If the added system complexity and cost can be justified, then every effort should be made to include a prototype regenerative braking system in any future hybrid vehicle in order to verify the energy recovery 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.

10.1.1.4.6* Impact of Regional Characteristics in Energy Sources for Electric Generating Power Plants

The results shown in Section 10.1.1.4.5 were derived for the nationwide mix of fuels for electric generating stations described in Section 6 of the report. 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 and little fossil fuel is consumed for this purpose. 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 energy consumption corresponding to three types of fuel sources: petroleum-based (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 10-42 through 10-45. 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 would be deficient on a fossil fuel basis. The New England and Middle Atlantic states reverse this situation and benefit more than the national average on fossil fuel and are deficient on petroleum-based fuels. Lastly, the West-South-Central states would receive fewer benefits than the nation as a whole for both types of fuel sources. The conclusions drawn here would hold equally well for the parallel configuration.

10.1.1.4.7 Lead-Acid versus 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 reliance would have to be placed on lead-acid battery systems. To ascertain the type of 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 10-46, where relative energy consumption is plotted versus 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.

10.1.1.4.8 Impact of Changes in Powertrain Component Characteristics

Although the component characteristics used in this study are considered valid and are based on data from contemporary designs, achievement of the individual efficiency levels simulated in analyses may not be possible when the components are integrated into the powertrain and operated under varying ambient road conditions. Because the conclusions drawn from

this study are dependent on the selected component characteristics, some insight into the impact of these characteristics on vehicle energy consumption is desirable. Hence, at maximum vehicle design range, variations were introduced into battery charge efficiency, differential gear/motor efficiency, and vehicle accessory/engine auxiliary load. The results are presented in the form of a ratio S , which is defined as the percent change in vehicle performance factor divided by the percent change in component characteristics. As an example, if a vehicle energy consumption change of 8 percent (say, from 2.5 to 2.7 kW-hr/mi) is caused by a 10 percent change in component efficiency (say, from 80 percent to 72 percent), then the S is equal to -0.8.

The sensitivity factor S is given in Table 10-3 for each of the component variations noted. The linearized results shown are only indicative of expected changes in vehicle performance because the interaction of all components and the complexity of the engine map produces nonlinear effects. Nonetheless, it is seen that, for the restricted case examined, changes in battery charge efficiency or vehicle accessory/engine auxiliary loads are not of great significance. The major impact seen is in changes to differential gear/motor efficiency.* This component-related efficiency change was selected for calculation simplicity, but it can also be thought of as a complex of efficiency changes throughout the powertrain. Therefore, designing motors and associated gear systems for high efficiency at part load is very important for a series configuration hybrid vehicle that is expected to demonstrate energy savings while meeting emission standards. Poor efficiency for this component could readily eliminate the energy savings at the vehicle operating ranges discussed previously.

Stationary electric generating plant efficiency, electric power transmission efficiency, and battery recharge efficiency are also factors that have a direct bearing on the results shown for energy consumption. An examination of one of these factors, powerplant generating efficiency, showed that changes in this parameter produced minor changes in vehicle energy consumption. For example, at the minimum operating range, if the generating efficiency were decreased by 10 percent (from 38 to 34.2 percent), then the ratio of hybrid to conventional vehicle energy consumption would

*Changes in differential gear ratio had little effect and were not summarized.

increase by only 3 percent for all fuels and about 1 percent for petroleum-based fuels. At greater vehicle operating range, however, the increase is less than 1 percent. Therefore, nationwide variations in this factor are generally not of concern in assessing the potential for energy savings with the hybrid heat engine/battery vehicle.

10.1.1.5 Summary of Hybrid Vehicle Exhaust Emission Characteristics

Vehicle-related exhaust emissions relative to 1975-76 federal standards were determined for the two car weights of 2500 and 4000 pounds and for the 6000-lb van operating over the EPA Urban Driving Cycle. These vehicle-related exhaust emissions refer to HC, CO, and NO_x emissions from the vehicle, as well as those from the electric generating plant* due to expenditure of fuel for providing battery recharge energy. Inclusion of vehicle-only emissions is helpful for ascertaining potential improvement in ambient air quality for communities with electric generating power plants in remote locations.

10.1.1.5.1 Impact of Design Peak Cruise Speed, Vehicle Weight, and Regenerative Braking

Relative emissions for the series configuration are presented in Figures 10-47 and 10-48 as a function of vehicle design range. Figure 10-47 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 10-48 shows the effect of vehicle weight for a design peak cruise speed of 65 mph. The 6000-lb van shows the poorest emissions, and the 2500-lb car shows 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

* Sulfur oxides and particulates were not evaluated.

design operating range. No such problem in meeting emission standards exists for the 2500-lb series configuration car.

The low emissions for HC and CO might not be totally unexpected. The General Motors 140-cubic-inch-displacement engine selected for the hybrid vehicle has shown markedly low values for these emissions when used in a conventionally powered car (Chevrolet Vega or Pontiac Astre) subjected to federal emissions test procedures (Ref. 10-1).

The NO_x emissions (gm/mi) 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 the heat engine characteristic whereby NO_x specific emissions (gm/hp-hr) increase as power output increases. Because HC and CO specific emissions generally have characteristics the inverse of NO_x (i.e., decreasing with increasing power), the gram per mile emissions of these pollutants appear to be almost independent of the design range.

The vehicle-related emissions analysis was extended to vehicles with parallel configuration powertrain and to those with regenerative braking. Because emissions of oxides of nitrogen appear to be the greatest problem in meeting the standard, it was selected for illustration. The results are presented in Figure 10-49.

The series configuration with 15 percent recovery of drive wheel energy shows significant reductions in the NO_x emissions. 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, and the 2500-lb car is well below the emission standard.

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 vehicle design range below 160 miles for all emission sources and below 210 miles for emissions just from 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.

The trends seen for emissions and energy consumption 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 reduction in NO_x emissions could be expected by operating the heat engine with a revised schedule of power versus rpm, but this would likely result in an increase in fuel energy expenditure, as well as a possible increase in HC and CO emissions. But, since these 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.

10.1.1.5.2 Impact of Regional Characteristics in Energy Sources for Electric Generating Power Plants

Because power plant sources contribute only a small fraction of the overall vehicle-related exhaust emissions, regional changes are not expected to have any major impact on the emission levels previously presented. A favorable reduction in emissions would be expected for the Pacific

Northwest, which relies so heavily on the relatively pollution-free hydroelectric power. In this case, the curves designated "vehicle only" would apply, regardless of the degree of reliance on electric generating plants for recharge energy.

10.1.1.5.3 Lead-Acid versus Nickel-Zinc Batteries

The vehicle-related exhaust emissions were also determined for a 4000-lb series configuration vehicle with lead-acid batteries in place of nickel-zinc batteries. The results relative to 1975-76 federal standards are presented in Figure 10-50. The emissions of HC and CO are not changed to any degree from the nickel-zinc systems, but there is a noticeable increase in NO_x .

10.1.1.5.4 Impact of Changes in Powertrain Component Characteristics

The sensitivity factor S was discussed previously in Section 10.1.1.4.8, and results were presented in Table 10-3. The effect of variations in component performance on exhaust emissions is also given in Table 10-3. It is seen that, for the restricted case examined, changes in battery charge efficiency are not of major significance to emissions results. Vehicle accessory/engine auxiliary loads are only of significance to HC and CO emissions, but, since these are generally well below emission standards, this is not of concern. The major impact seen is in changes to differential gear/motor efficiency. Poor efficiency for these powertrain elements could have a significant effect on vehicle emissions.

10.1.2 Analysis for EPA Highway Driving Cycle

10.1.2.1 Cycle and Vehicle Propulsion Characteristics

The highway cycle is for the most part represented by nearly steady cruise speeds, ranging from about 45 to 60 mph, accompanied by mild acceleration/deceleration rates except at commencement and termination of the cycle, when the rates reach almost 5 mph/second. The cycle covers 10.2 miles in a period of 765 seconds, resulting in an average speed of 48.0 mph.

The velocity history is shown in Figure 10-51 and the acceleration history in Figure 10-52. The corresponding vehicle drive wheel

power requirements for a 4000-lb car are shown in Figure 10-53. While the total power required (cruise plus acceleration) is not much different from the urban cycle, the cruise power levels alone are considerably higher.

10.1.2.2 Powertrain Component Characteristics

The engine power-rpm restriction used in the EPA Urban Driving Cycle for balancing fuel consumption and emissions was left unchanged for the EPA Highway Driving Cycle. With the higher cruise power levels on this cycle, the engine is required to operate at much higher power and rpm than in the urban cycle (see Figures 10-54 and 10-55), and this form of operation could only change if the restricted power-rpm curve were revised.

The cruise power characteristics, when combined with the mild accelerations, mean that little energy is transferred into and out of the battery and that most of the energy expenditure takes place by high-level power transfer in the engine-generator-motor-wheels circuit for the series configuration or in the engine-transmission-wheels circuit for the parallel configuration. While such routes are more efficient than passage of power through the battery, other complicating factors, as discussed in subsequent sections, enter into the consumption of energy. In addition, there is far less reliance on electric generating power plants, because little energy is extracted from the batteries.

10.1.2.3 Summary of Hybrid Vehicle Energy Consumption Characteristics

10.1.2.3.1 4000-lb Car

The energy consumption characteristics of the 4000-lb heat engine/battery hybrid vehicle operated over the EPA Highway Driving Cycle are illustrated in Figure 10-56. The energy consumption of the hybrid vehicle is referenced to the gasoline energy consumption of the 4000-lb conventional baseline vehicle over the same cycle (at 19.4 mpg or 1.74 kW-hr/mi as given in Section 7).

10.1.2.3.1.1 Series Configuration

The series configuration (Figure 10-56a) 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 a number of 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). 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 which 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 the vehicle/accessory/engine auxiliary loads which can consume up to 15 percent of the total engine energy output. This arises from the fact that accessory/auxiliary loads are a function of engine speed, and the hybrid vehicle uses small engines that must operate at high speed in order 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.

10.1.2.3.1.2 Parallel Configuration

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 is used to provide 100 percent of the battery recharge energy (Figure 10-56b). 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 ($\gamma \leq 0.35$), gasoline usage is conserved when compared to the baseline vehicle. At γ levels below 0.2, total energy savings also result.

10.1.2.3.1.3 Regenerative Braking Effects

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 the minimal number of vehicle decelerations for this driving cycle. Therefore, the effect of regenerative braking on energy consumption for either the series or parallel configuration is negligible.

10.1.2.3.2 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 10-57. Here, the basis of comparison is the gasoline energy consumption of the 2500-lb vehicle (31.0 mpg or 1.09 kW-hr/mi as given in Section 7). The basic effects of configuration (series versus parallel) and of regenerative braking are similar to those described for the 4000-lb car.

10.1.2.3.3 6000-lb Van

Figure 10-58 depicts the energy consumption characteristics of the 6000-lb hybrid van, as compared with the gasoline energy consumption of the baseline vehicle (14.1 mpg or 2.4 kW-hr/mi as given in Section 7). Again, the basic effects of configuration and of regenerative braking are similar to those described for the 4000- and 2500-lb vehicles. In the case of the 6000-lb van, however, even the parallel-configured hybrid vehicle uses more gasoline and total energy than the reference baseline vehicle 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.

10.1.2.3.4 Impact of Vehicle Weight

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

The results of the analysis are illustrated in Figure 10-59. 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 solely for comparison purposes, since it exceeds the conventional vehicle energy consumption throughout the vehicle design range shown.

10.1.3 Analysis for U.S. Postal Service Driving Cycle

10.1.3.1 Cycle and Vehicle Propulsion Characteristics

The U.S. Postal Service Driving Cycle is characterized by a series of repetitive mild accelerations (2 mph/second) to various low level speeds (10 to 20 mph), with each acceleration followed by a coasting period, a sharp deceleration (braking at almost 5 mph/second), and a stop. A vehicle on this cycle covers a distance of 0.542 miles in 228 seconds for an average speed of about 8.6 mph.

The velocity history is shown in Figure 10-60 and the acceleration history in Figure 10-61. The associated vehicle drive wheel power required for a 4000-lb car is given in Figure 10-62. The vehicle speeds and power requirements are quite small and would require only very small components in the powertrain. Because the powertrain design remained unchanged from that established for vehicle cruise speeds of 55 mph and greater, the analysis results shown herein might be expected to have some margin for improvement in efficiency.

10.1.3.2 Powertrain Component Characteristics

Component characteristics are briefly illustrated for a 4000-lb car designed for 65-mph peak cruise speed. Heat engine power requirements for vehicle propulsion over this cycle are exceedingly small. Figure 10-63 shows the power level needed for ensuring complete battery recharge ($\gamma = 1.0$) at the end of the cycle; it is only about 7 hp. The engine speed for this power level is almost 1100 rpm (Figure 10-64). At lower levels of γ , the power and rpm are even lower, and the BSFC rises to less favorable values.

Correspondingly, the electric drive motor power and speed (Figures 10-65 and 10-66) are quite low compared to values found for the EPA Urban Driving Cycle. The motor efficiency seen in Figure 10-67 is also quite low because of the low power-low rpm operation. Were the system to have been designed for this type of operation with limited maximum cruise speed (say, 45 to 55 mph), the efficiency could be expected to improve.

10.1.3.3 Summary of Hybrid Vehicle Energy Consumption Characteristics

10.1.3.3.1 4000-lb Car

The fuel energy consumption characteristics of the 4000-lb heat engine/battery hybrid vehicle are depicted in Figure 10-68 for vehicle operation over the U.S. Postal Service Driving Cycle. The energy consumption of the hybrid vehicle has been referenced to the gasoline energy consumption given in Section 7 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.

10.1.3.3.1.1 Series Configuration

As seen in Figure 10-68a, the hybrid vehicle uses much less energy than the conventional car at all values of γ . 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 by wall-plug electricity, the hybrid heat engine energy consumption

continues to decline with a minimum of 40 percent gasoline required in the vicinity of $\gamma = 0.2$. This trend holds as well for the overall hybrid energy consumption (tanked onboard gasoline plus the recharge energy generated by fuel consumption at the utility power plant) with a minimum of 55 percent energy consumption. The rise in energy consumption for lower values of γ is due, as noted previously in the discussion of the urban cycle, to the onset of poor engine efficiency at very low engine power levels.

10.1.3.3.1.2 Parallel Configuration

As seen in Figure 10-68b, 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.

10.1.3.3.1.3 Regenerative Braking Effects

Figures 10-68c and 10-68d 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 shows some further decreases in energy consumption to 62 percent 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.

10.1.3.3.2 2500-lb Car

The energy consumption characteristics of the 2500-lb heat engine/battery hybrid vehicle over the U.S. Postal Service Driving Cycle

are illustrated in Figure 10-69. Here, the basis of comparison is the gasoline energy consumption of the 2500-lb vehicle (12.4 mpg or 2.72 kW-hr/mi as given in Section 7). As can be seen, the comparative effects of series versus parallel configurations and of various degrees of regenerative braking are similar to those described for the 4000-lb car.

10.1.3.3.3 6000-lb Van

Figure 10-70 depicts the energy consumption characteristics of the 6000-lb hybrid vehicle as compared with the gasoline energy consumption of the baseline vehicle (5.3 mpg or 6.34 kW-hr/mi as given in Section 7). Again, the basic effects of configuration and of regenerative braking are similar to those described above for the 4000- and 2500-lb hybrid vehicles.

10.1.3.3.4 Impact of Vehicle Weight and Regenerative Braking

Energy consumption for three series configuration vehicle weights is presented as a function of vehicle design operational range in Figure 10-71. The energy savings over a conventional vehicle are quite remarkable and, even at large design 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 10-72 through 10-74 for the series configuration and 10-75 through 10-77 for the parallel configuration. With 30 percent recovery of vehicle drive wheel energy, the total energy consumption of the 4000-lb series configuration vehicle is less than half that of the conventional vehicle even at design operating range as large as 200 miles. For design operating range limited to about 100 miles, there is about a 60 percent savings in petroleum-based fuel. Additional savings are available with the parallel configuration.

The sharp rise in energy consumption at the lowest range is due to the poor engine efficiency at very low power operation producing a very rapid rise in BSFC and, therefore, higher fuel consumption than found at somewhat greater engine power levels. 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 U.S. Postal Service Driving Cycle is very evident. In contrast to

the EPA Urban Driving Cycle or EPA Highway Driving 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 multistop delivery cars, vans, or trucks with operating range requirements that exceed the capabilities of all-electric powertrains.

10.2 ENERGY CONSUMPTION AND EXHAUST EMISSIONS FOR HEAT ENGINE/FLYWHEEL HYBRID VEHICLES

Hybrid vehicle characteristics are presented as a function of time for a 4000-lb series configuration car with a design cruise speed of 65 mph and a steel flywheel energy storage system. Other cruise speeds, vehicle weights, and powertrain configurations are discussed in regard to the integrated results that summarize vehicle-related energy consumption and exhaust emissions.

10.2.1 Analysis for EPA Urban Driving Cycle

10.2.1.1 Cycle and Vehicle Propulsion Characteristics

The characteristics described in Section 10.1.1.1 apply equally as well to flywheel systems and are not repeated here.

10.2.1.2 Powertrain Component Characteristics

In the same manner as the presentation in Section 10.1.1.2 for battery systems, component characteristics are given as a function of time throughout the driving cycle for two different fixed minimum power settings of the output of the transmission that is located between the heat engine and the flywheel. Because of slight changes in the transmission efficiency, the corresponding minimum power setting of the heat engine is not fixed, and varies slightly throughout the driving cycle. However, this approach matches that for the battery system from the standpoint of delivering fixed power levels to the energy storage system.

Because the energy storage capacity of the steel flywheel in this study is quite small compared with that for the battery system, the flywheel energy would be depleted before the end of the EPA Urban Driving

Cycle, if no heat engine recharge power were available. Therefore, a minimum power setting of about 5.5 hp for propulsion was the lowest the system could tolerate. The higher value for minimum power setting was 11.4 hp, and this power was sufficient to provide a fully recharged flywheel at the end of the driving cycle. This power level is significantly less than that for the battery system and is due to the superior efficiency of the fly-wheel system.

Heat engine speed and power delivery histories are presented along with accessory/auxiliary power demands in Figures 10-78 through 10-81. At the lower power setting, the engine rpm is only about 850 rpm (Figure 10-78), the power for propulsion is about 5.5 hp (Figure 10-79), the engine auxiliary/vehicle accessory power demand is about 1.6 hp (Figure 10-80), and the total engine power output is then about 7 hp (Figure 10-81). Figure 10-82 shows the total shaft energy expended by the engine is about 3 kW-hr.

Under the lower minimum power setting, the engine must quite often increase power output and speed above the minimum level in order to meet most of the vehicle cruise power demands. Therefore, except at very low speeds or when the vehicle is stationary, the engine is forced to undergo considerable speed and power changes (but not nearly as often as for the battery system where the engine minimum power could be set at zero). At the higher minimum power setting, these variations are largely diminished as seen in Figures 10-83 through 10-86. Figure 10-83 shows an engine speed of about 1050 rpm, Figure 10-84 shows power for propulsion of about 9.6 hp, Figure 10-85 shows engine auxiliary/vehicle accessory power demands of about 1.7 hp, Figure 10-86 shows total engine power output of about 11.3 hp, and Figure 10-87 shows a total engine energy expended at the shaft of about 3.8 kW-hr.

In regard to the power output history of the transmission that connects the engine to the flywheel, the same trends are seen by comparing the two power settings in Figures 10-88 and 10-89. The difference between these power levels and those for the heat engine is due somewhat to the intermediate gearing between the engine and the transmission, but primarily due

to the transmission efficiency, which is displayed as a function of time in Figures 10-90 and 10-91. The efficiency at the lower engine power setting lies largely between 80 and 88 percent. The efficiency at the higher engine power setting has improved to a range of 88 to 91 percent. This improvement is due to an increase in input speed to the transmission. Similar efficiency levels for the lower power setting could have been achieved if the engine-transmission intermediate gearing speed ratio had been changed. To simplify making computer runs and to avoid devoting excessive time to system optimization, the gear ratio is fixed. However, the results seen here point out the importance of gear ratio selection and system optimization on the overall powertrain efficiency.

The flywheel characteristics are displayed in Figures 10-92 through 10-105. At the lower engine power setting, the flywheel speed decays from 24,600 rpm to about 5000 rpm at the end of the driving cycle (Figure 10-92). The flywheel power input level of about 4.5 hp is shown in Figure 10-93; the characteristics are very similar to the transmission output characteristics and differ only in the efficiency of the intermediate gearing. Flywheel power output is shown in Figure 10-94, and the wide variation in power is in marked contrast to the input power level because of the need to respond to vehicle drive wheel power demands. The parasitic power loss of the wheel due to windage, bearings, etc. is shown in Figure 10-95, and ranges from 1.4 down to 0.5 hp at the low wheel speed found at the end of the cycle. This power loss should be examined very carefully in any system design because it constitutes a significant part of the energy extracted from the flywheel for vehicle propulsion (Figure 10-96), and it forms a large fraction of the energy stored in the flywheel. The stored energy in the flywheel is shown in Figure 10-97 with a decay from 605 W-hr down to almost zero energy remaining. Figure 10-98 shows this energy storage history as a percentage of the initial storage value. Because a minimum decay level for the wheel was set at 25 percent of the initial value, this is not an acceptable operating condition for the vehicle. The heat engine power for propulsion should be increased 45 percent to about 8 hp in order to prevent the energy storage from falling below 25 percent of the initial value.

Figures 10-99 through 10-105 present a similar set of curves for the higher engine power setting. The primary differences noted when contrasted with the lower power setting are:

- a. The flywheel speed is maintained relatively constant and does not fall below 21,000 rpm.
- b. At some intervals, the flywheel speed rises above the base level of 24,600 to 25,400 rpm and this overspeed condition must be accounted for in the wheel design or in the system operation.
- c. The flywheel power (or energy) extracted for vehicle propulsion differs only slightly from the results for the lower engine power setting because of small changes in transmission efficiency (to be discussed next).

The transmission linking the flywheel to the vehicle drive wheels (intermediate gearing and differential also required) must undergo a much more varied speed-torque-power history than the unit that transfers power from the heat engine to the flywheel. However, it maintains good efficiency for both engine power settings, as shown in Figures 10-106 and 10-107, with values generally ranging from 80 to 90 percent. The slight differences seen in comparing these figures are due to the differences in flywheel speed (resulting in differences in transmission input speed) at any given time point in the driving cycle. Very low values of efficiency (down to a few percent) are present briefly when the vehicle is accelerating from a stop. Except for these isolated instances, the transmission efficiency is quite high. Considering that no attempt was made to optimize the gear ratios in the powertrain, it shows the remarkable flexibility in performance for a continuously varying transmission.

10.2.1.3 Example of Analysis Results

Just as for the battery-type hybrid, examples of the analysis results are presented here as a function of γ for a 4000-lb vehicle.

Engine shaft power used for propulsion purposes only is shown in Figure 10-108; it varies from about 5.5 to 9.5 hp, being much lower than for the battery system at equivalent values of γ . Similar lower values are found for the energy required to be provided by the engine fuel which is a maximum of about 16.4 kW-hr at $\gamma = 1.0$ (Figure 10-109).

The flywheel speed was not restricted to its initial value of 24,600 rpm, and energy from the engine entering at speeds above this level was not counted as wasted energy. Therefore, no such curve is presented. The strength margin of safety for the wheel could permit a small degree of overspeed, whereas in the battery, when it is fully charged, there is no means for accepting additional energy and this energy must be wasted.

Vehicle propulsion energy that is provided by various fuel sources is presented as a ratio to fuel energy required for a conventionally powered 4000-lb car in Figure 10-110. It is seen that, regardless of whether the energy from petroleum-based fuels or from all fuels is used as a measure of performance, the heat engine/flywheel hybrid vehicle is more efficient than the conventionally powered vehicle at all values of γ .

10.2.1.4 Summary of Hybrid Vehicle Energy Consumption Characteristics

Energy consumption characteristics of the flywheel system 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 is also discussed.

The results of the analysis 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 result 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.

10.2.1.4.1 4000-lb Car

Analytical results giving the ratio of hybrid vehicle energy consumption to conventionally powered vehicle energy consumption are given in Figure 10-111 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 parameterized 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 configuration without regenerative braking, the energy consumption is less than for a conventionally powered car at all values of γ ; (c) the range of γ is considerably less than for the battery system due to the nature of power transfer wherein all energy supplied by the heat engine passes through the flywheel and all energy to the vehicle drive wheels is delivered by the flywheel; (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 10-111a, 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 is due to the combination of high efficiency elements in the powertrain and a heat engine operating near maximum efficiency. In Figure 10-111b, 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 10-111c). 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 brief 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.

10.2.1.4.2 2500-lb Car

Results for this weight vehicle are presented in Figure 10-112 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 10-112a). The greatest fuel savings are again shown by the parallel configuration with 15 percent recovery of drive wheel energy. As shown in Figure 10-112d, its relative energy consumption is only 77 percent at $\gamma = 1.0$.

10.2.1.4.3 6000-lb Van

Slightly lower values for energy expenditure are shown by the van in Figure 10-113. 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 10-113d for the parallel configuration with 15 percent driving cycle energy recovered and the onboard engine providing all recharge energy.

10.2.1.4.4 Impact of Design Peak Cruise Speed, Design Peak Acceleration, and Vehicle Weight

For the purpose of showing parametric effects, analytical results for the series configuration were plotted as a function of vehicle design operating range and are presented in Figure 10-114. 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 design operating range less than 50 miles. Hence, in contrast to the heat engine/battery system, the heat 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 at this point 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.

10.2.1.4.5 Impact of Regional Characteristics in Energy Sources for Electric Generating Power Plants

Because the heat engine/flywheel vehicle is not expected to be designed for reduced operating range where electric generating power plant energy supplies become a factor for consideration, no analyses are presented for impact on energy consumption of geographic variations in power plant fuel consumption characteristics.

10.2.1.4.6 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. Two installations were selected. One was a 1.436-foot-diameter engine-in-line design of the type selected by Lockheed, and the other was a 2.0-foot-diameter vertical-axis design of the type selected by Johns Hopkins (see Section 3.2). The pertinent design speeds, energy densities, etc., for these Kevlar wheels can be found in Section 5.4.

An initial evaluation showed that these flywheels resulted in totally unacceptable performance because of excessive parasitic losses related to aerodynamic drag, bearing drag, seal drag, and vacuum pump power requirements. At design speed, the smaller of the two wheels had a total parasitic loss of about 11 hp, most of which was related to windage and the vacuum pump. Hence, a large amount of engine power was required to keep the wheel recharged, and this resulted in energy consumption 75 percent higher than for a conventionally powered car. The larger wheel proved to have even greater losses.

Attempting to lower the pressure 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.

The component performance histories of interest are shown in Figures 10-115 through 10-120 for the 2.0-foot-diameter rotor. Gear ratios had to be revised, of course, to permit the transmissions to accept

the much higher speed levels of the plastic rotor system. Generally, the transmission efficiencies (Figures 10-115 and 10-120) are comparable to those for the steel rotor system.

With the much greater energy storage capability of the plastic rotor system (Figures 10-118 and 10-119), the rotor speed variation (Figure 10-116) is less than for the steel rotor system. However, the parasitic losses shown in Figure 10-117 are about 4.5 hp and are still considered excessive for this system.

The hybrid system relative energy consumption is plotted versus vehicle design range in Figure 10-121 for a 4000-lb series configuration car operating over the EPA Urban Driving Cycle. As can be seen, 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, but only slightly from about 7.5 miles for the steel wheel to 17.5 miles for the Kevlar wheel.

Therefore, high-speed plastic wheels do not appear to be a viable system for the heat engine/flywheel hybrid vehicle, unless parasitic losses could 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 mainly 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.

10.2.1.4.7 Impact of Changes in Powertrain Component Characteristics

The results of the analysis are somewhat similar to those for the battery system in that changes in the differential gear/transmission efficiency created the largest changes to energy consumption (see Table 10-4). Compared to the battery system, however, the effect on energy is far less.

Other elements in the powertrain can produce changes similar to those generated by the gear/transmission. Therefore, component design efficiencies must be verified to ensure that the hybrid vehicle will meet the performance projected for it in this study.

No significant changes in energy consumption or emissions were discernible when differential gear ratio was varied ± 10 percent.

10.2.1.5 Exhaust Emission Characteristics

As noted previously, an evaluation of exhaust emissions for the hybrid vehicle relative to 1975-76 federal standards is pertinent only to the urban driving cycle because it is for this cycle that emission standards have been specified by the federal government. Results of the analysis of relative exhaust emissions 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 10-122 and 10-123. In contrast to the energy consumption characteristics, the emissions are strongly affected by vehicle weight and cruise speed.

Figure 10-122 shows the effect of design cruise speed for a 4000-lb car. It is seen that the higher design cruise speeds give lower emissions; in fact, design cruise speeds of greater than 65 mph 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 10-123. 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 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.

10.2.2 Analysis for EPA Highway Driving Cycle

10.2.2.1 Cycle and Vehicle Propulsion Characteristics

The cycle and vehicle propulsion characteristics were presented previously in Section 10.1.2.1.

10.2.2.2 Powertrain Component Characteristics

The effect of high vehicle speeds on powertrain operation creates the same need for high engine power coupled with high engine speed, as was evident for the heat engine/battery hybrid. This is seen in Figure 10-124, which shows engine shaft power output that is used for vehicle propulsion on a 4000-lb series configuration car.

Transmission efficiencies for the series configuration are given in Figures 10-125 and 10-126. The efficiency levels are quite high, particularly for the transmission linking the flywheel to the vehicle drive wheels (T3). Under these conditions, the series configuration flywheel hybrid car can be expected to have greater energy consumption than the conventionally powered car, because at highway speeds the engine in the conventional system will be operating at efficiencies as high as those for the hybrid system and power is transferred through only one transmission rather than two transmissions. The parallel configuration, however, does circumvent this problem by providing an alternate power flow path to the rear wheels through one transmission.

10.2.2.3 Summary of Hybrid Vehicle Energy Consumption Characteristics

Analysis results for series and parallel configurations in three vehicle weights are presented in Figures 10-127, 10-128, and 10-129. In all cases, the γ range is very small and, as explained in Section 10.2.1.4.1, 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 γ values very close to 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 10-127a, fuel consumption for the 4000-lb series configuration car exceeds that for the conventionally powered car by about 16 percent. The parallel configuration (Figure 10-127b) 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 10-128). Similarly, for the 6000-lb van (Figure 10-129), 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.

10.2.3 Analysis for U.S. Postal Service Driving Cycle

10.2.3.1 Cycle and Vehicle Propulsion Characteristics

These characteristics were shown previously in Section 10.1.3.1.

10.2.3.2 Powertrain Component Characteristics

As was true for the battery system, the engine power requirements are very modest. As seen in Figure 10-130, only about 5.5 hp is needed over most of the cycle for propulsion needs of a 4000-lb vehicle and to fully recharge the flywheel. The flywheel parasitic losses are still about 1.4 hp on this cycle. Energy dissipated in this manner is now about 25 percent of that expended at the engine shaft for propulsion needs. At the low engine power levels on this cycle, flywheel parasitic losses assume even more importance.

Figures 10-131 and 10-132 show the transmission efficiency histories. The levels are generally lower than seen on the EPA Urban or Highway Driving Cycle, particularly for the transmission delivering power to the drive wheels (T3). This is due to the continual start-stop type of vehicle operation that causes the transmission to operate at speed and torque ratios well off design. Some improvement might be expected if the gear ratios between components were revised from those values found satisfactory for the EPA cycles.

10.2.3.3 Summary of Hybrid Vehicle Energy Consumption Characteristics

As in Sections 10.2.1.4 and 10.2.2.3, 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 10-133, 10-134, and 10-135, 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 10-133a 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 2500-lb car are shown in Figure 10-134 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 10-135 to be about 46 and 55 percent.

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.

10.3 REFERENCES

- 10-1. D. T. West, et al., "A Technical Report of the 1975 Union 76 Fuel Economy Tests," Union Oil Company of California, SAE Paper No. 750670, Presented at Society of Automotive Engineers West Coast Meeting, Seattle, Wash., August 11-14, 1975.

TABLE 10-1. MATRIX FOR PARAMETRIC COMPUTER RUNS: HYBRID HEAT
ENGINE/BATTERY VEHICLE, SERIES CONFIGURATION

Vehicle Weight (lb)	Vehicle Maximum Cruise Speed (mph)	Driving Cycle	Differential Gear Ratio	Combined Differential Gear/Motor Efficiency Factor	Accessory Load Factor	Battery Charge Efficiency from Power Plant/ Onboard Generator	Type of Battery
4000	80	EPA Urban	2.73	0.980	1.0	0.8/0.7	Nickel-Zinc
→ 2500	65	→	→	→	→	→	→
6000	55	→	→	→	→	0.72/0.7	→
4000	65	→	→	→	→	0.72/0.63	→
→ 2500	→	→	→	0.882	→	0.88/0.77	→
6000	→	→	3.55	1.078	→	0.8/0.7	→
4000	→	→	1.91	0.980	0.9	→	→
→ 2500	→	EPA Highway	2.73	→	1.1	→	→
6000	→	→	→	→	1.0	→	→
4000	→	Postal Service	→	→	→	→	→
2500	→	→	→	→	→	→	→
6000	→	→	→	→	→	→	→
4000	→	EPA Urban	→	→	→	→	Lead-Acid

TABLE 10-2. MATRIX FOR PARAMETRIC COMPUTER RUNS: HYBRID HEAT
ENGINE/FLYWHEEL VEHICLE, SERIES CONFIGURATION

Vehicle Weight (lb)	Vehicle Maximum Cruise Speed (mph)	Driving Cycle	Differential Gear Ratio	Combined Differential Gear/Transmission Efficiency Factor	Accessory Load Factor	Flywheel Spinup Motor Efficiency	Flywheel Characteristics R/N/E ^a	Type of Flywheel
4000	80	EPA Urban	2.73	0.980	1.0	0.90	0.544/24.6/605	Steel Wheel
2500	65							
6000	55						0.493/27.2/450	
4000	65						0.593/22.6/781	
							0.544/24.6/605	
				0.882		0.81		
				1.078		0.72		
				0.980		0.90		
		EPA Highway	2.56		0.8		0.493/27.2/450	
2500			1.92		1.2		0.593/22.6/781	
6000			2.73		1.0		0.544/24.6/605	
4000		Postal Service					0.493/27.2/450	
2500							0.593/22.6/781	
6000		EPA Urban					0.718/58.5/2370	Kevlar Wheel
4000		EPA Urban					1.0/42.0/6395	Kevlar Wheel
4000								

^aR = wheel radius, ft; N = wheel speed, 1000 rpm; E = energy stored, W-hr

TABLE 10-3. SENSITIVITY OF VEHICLE PERFORMANCE TO POWERTRAIN COMPONENT CHARACTERISTICS: EPA URBAN DRIVING CYCLE, 4000-LB HEAT ENGINE/BATTERY CAR, SERIES CONFIGURATION, 65-MPH DESIGN PEAK CRUISE SPEED

Component Characteristic	S at Maximum Vehicle Design Range ^a			
	Energy (all fuels)	HC Emissions	CO Emissions	NO _x Emissions
Battery Charge Efficiency	-0.39	-0.25	-0.11	-0.28
Differential Gear/Motor Efficiency	-0.90	-1.66	-1.86	-1.05
Vehicle Accessory/Engine Auxiliary Load	+0.10	+0.73	+0.85	+0.18
^a $S = \frac{\% \text{ change in vehicle performance factor}}{\% \text{ change in component characteristic}}$				

TABLE 10-4. SENSITIVITY OF VEHICLE PERFORMANCE TO POWERTRAIN COMPONENT CHARACTERISTICS: EPA URBAN DRIVING CYCLE, 4000-LB HEAT ENGINE/FLYWHEEL CAR, SERIES CONFIGURATION, 65-MPH DESIGN PEAK CRUISE SPEED

Component Characteristic	S at Maximum Vehicle Design Range ^a			
	Energy (all fuels)	HC Emissions	CO Emissions	NO _x Emissions
Differential Gear/Transmission Efficiency	-0.48	-1.38	-0.99	-1.48
Vehicle Accessory/Engine Auxiliary Load	0.16	0.55	0.18	0.31
^a $S = \frac{\% \text{ change in vehicle performance factor}}{\% \text{ change in component characteristic}}$				

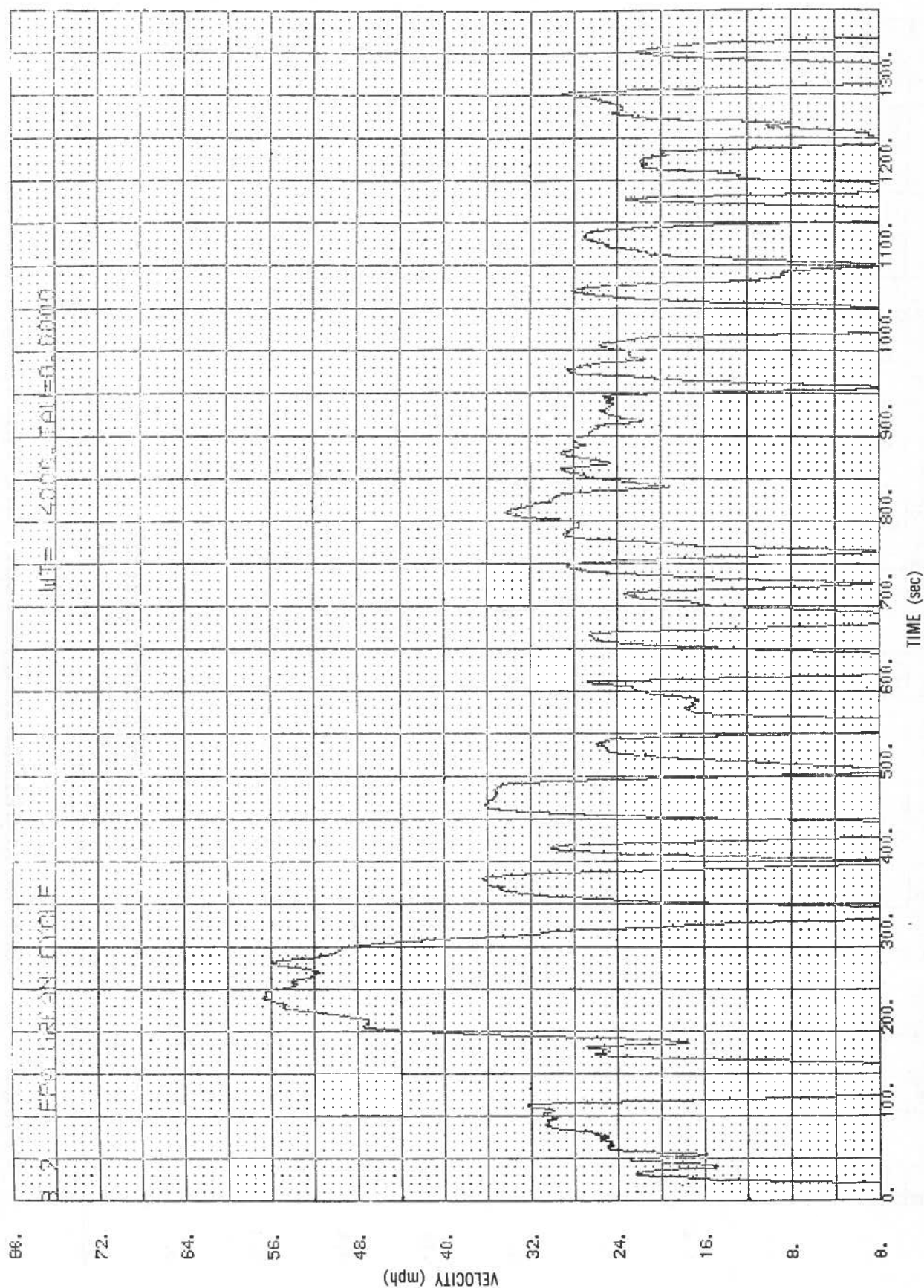


FIGURE 10-1. VEHICLE VELOCITY HISTORY: EPA URBAN DRIVING CYCLE

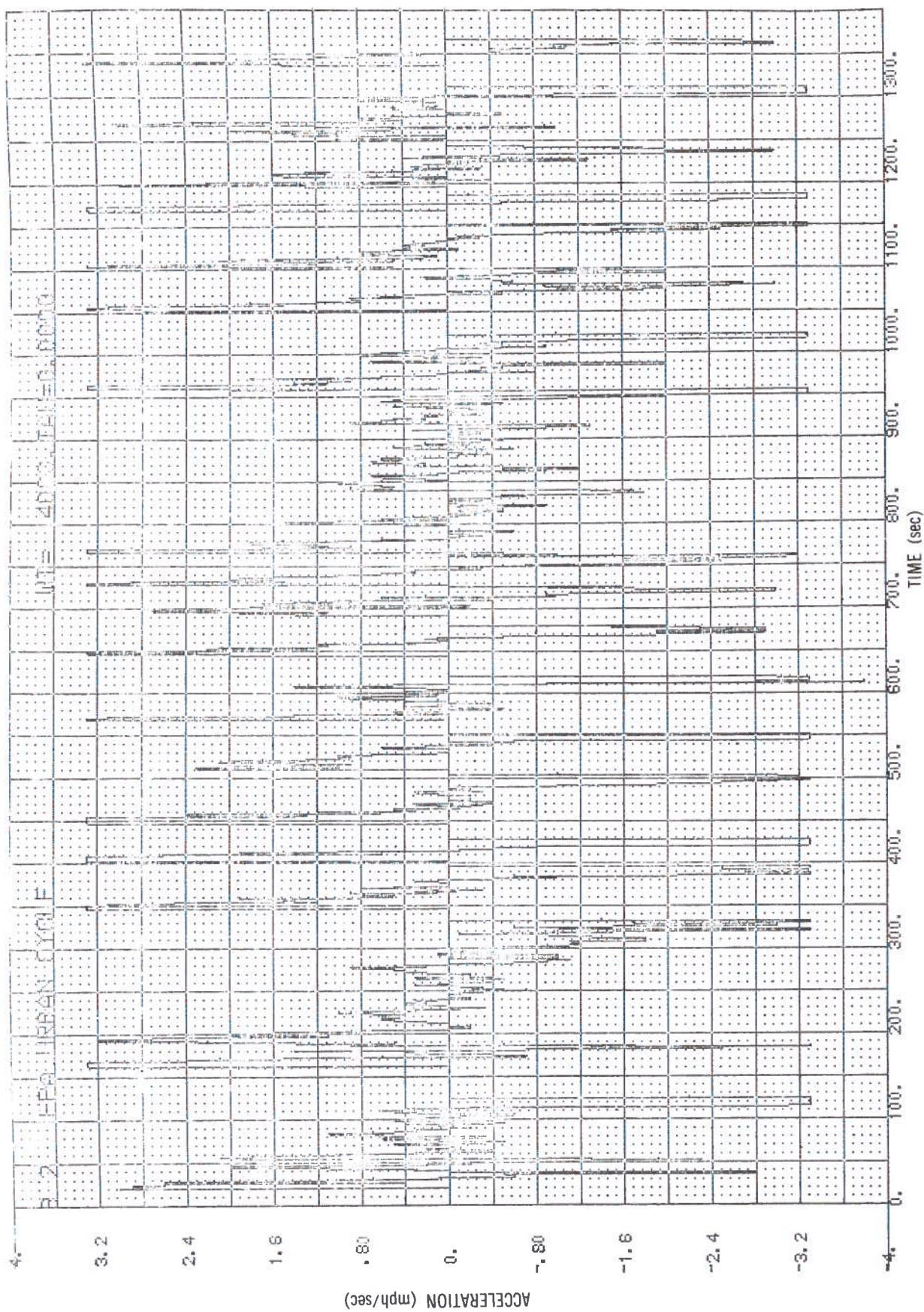


FIGURE 10-2. VEHICLE ACCELERATION HISTORY: EPA URBAN DRIVING CYCLE

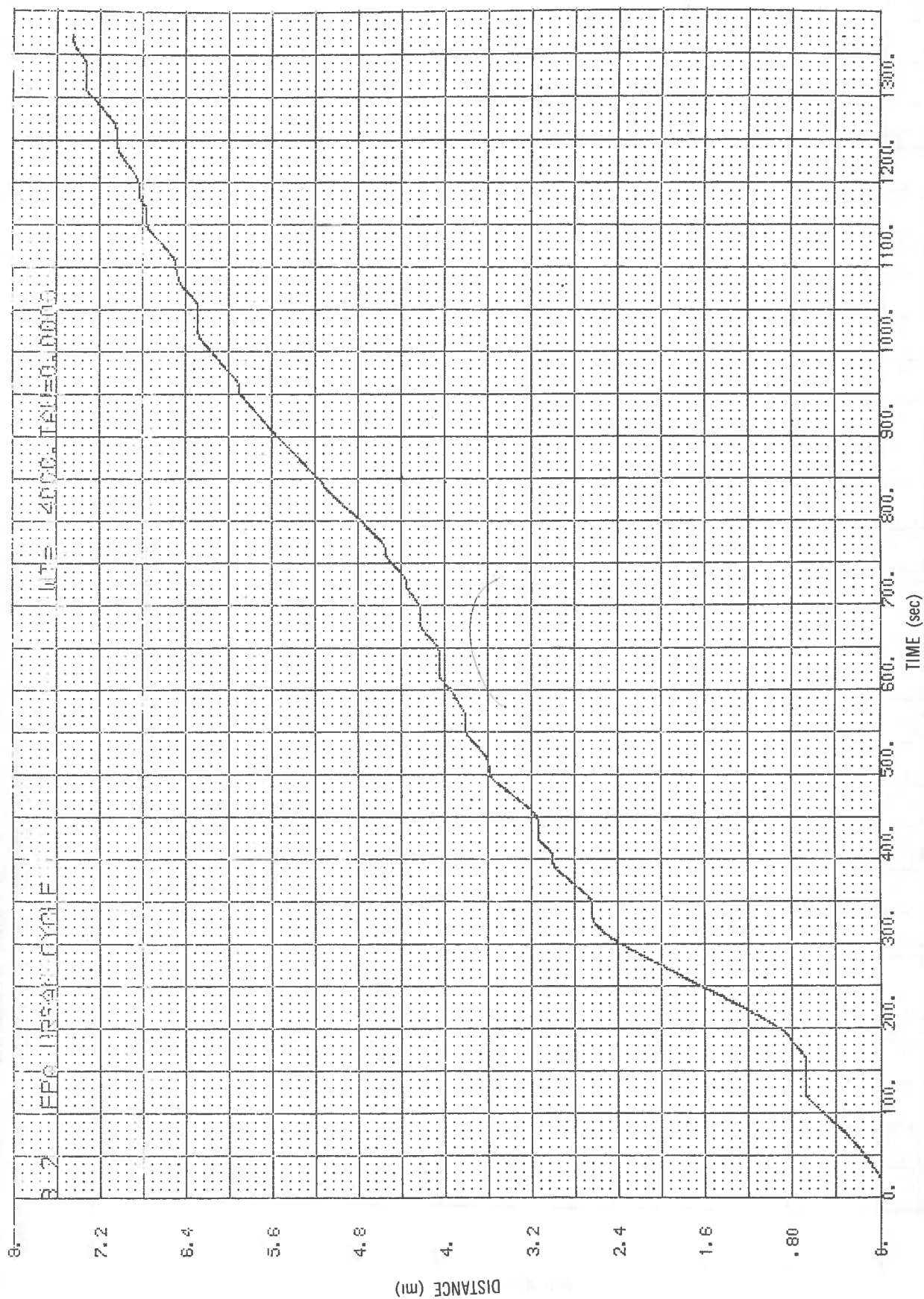


FIGURE 10-3. HISTORY OF DISTANCE TRAVELED: EPA URBAN DRIVING CYCLE

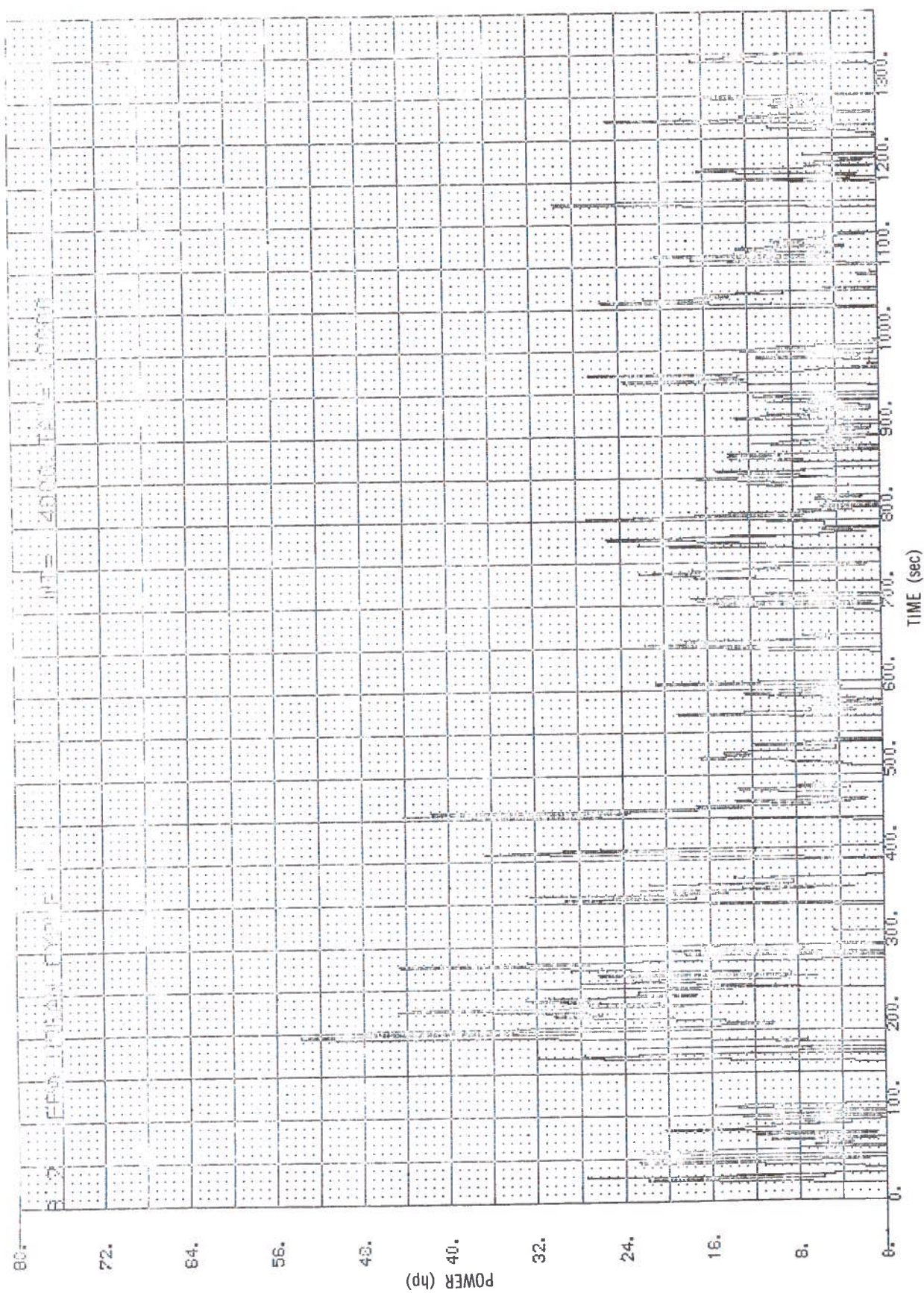


FIGURE 10-4. HISTORY OF TOTAL WHEEL POWER REQUIRED BY 4000-LB CAR ON EPA URBAN DRIVING CYCLE

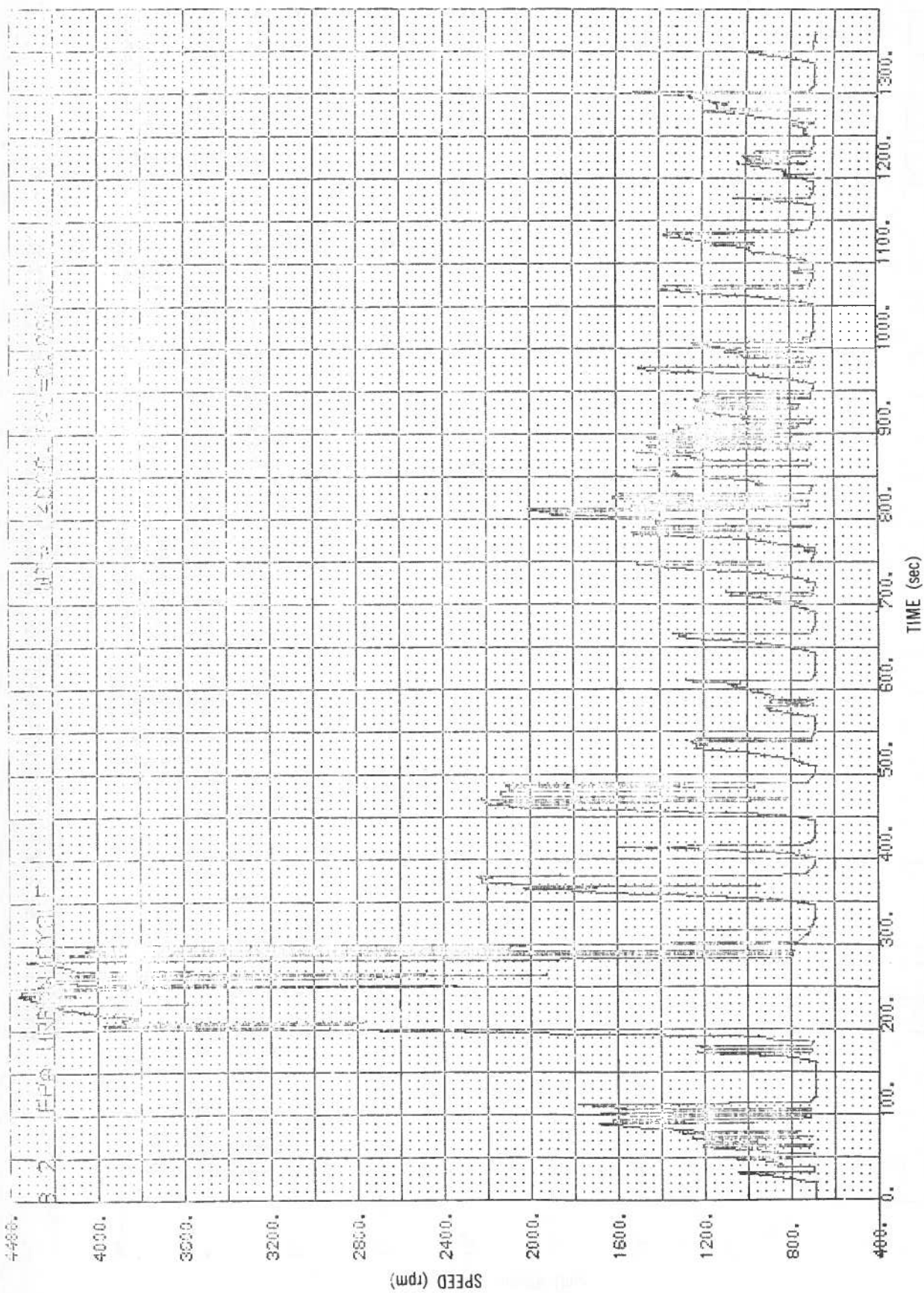


FIGURE 10-5. ENGINE SPEED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0$

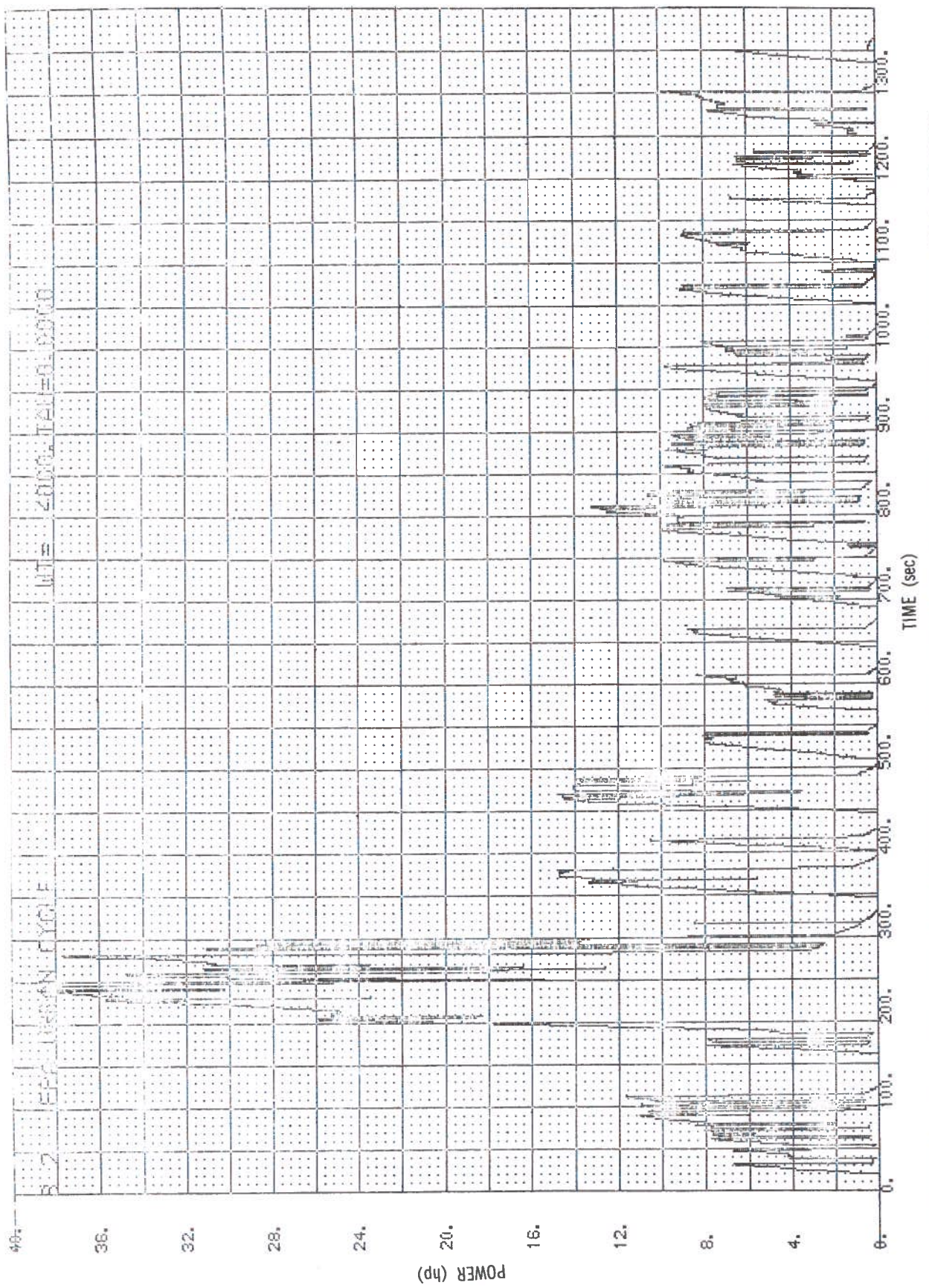


FIGURE 10-6. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0$

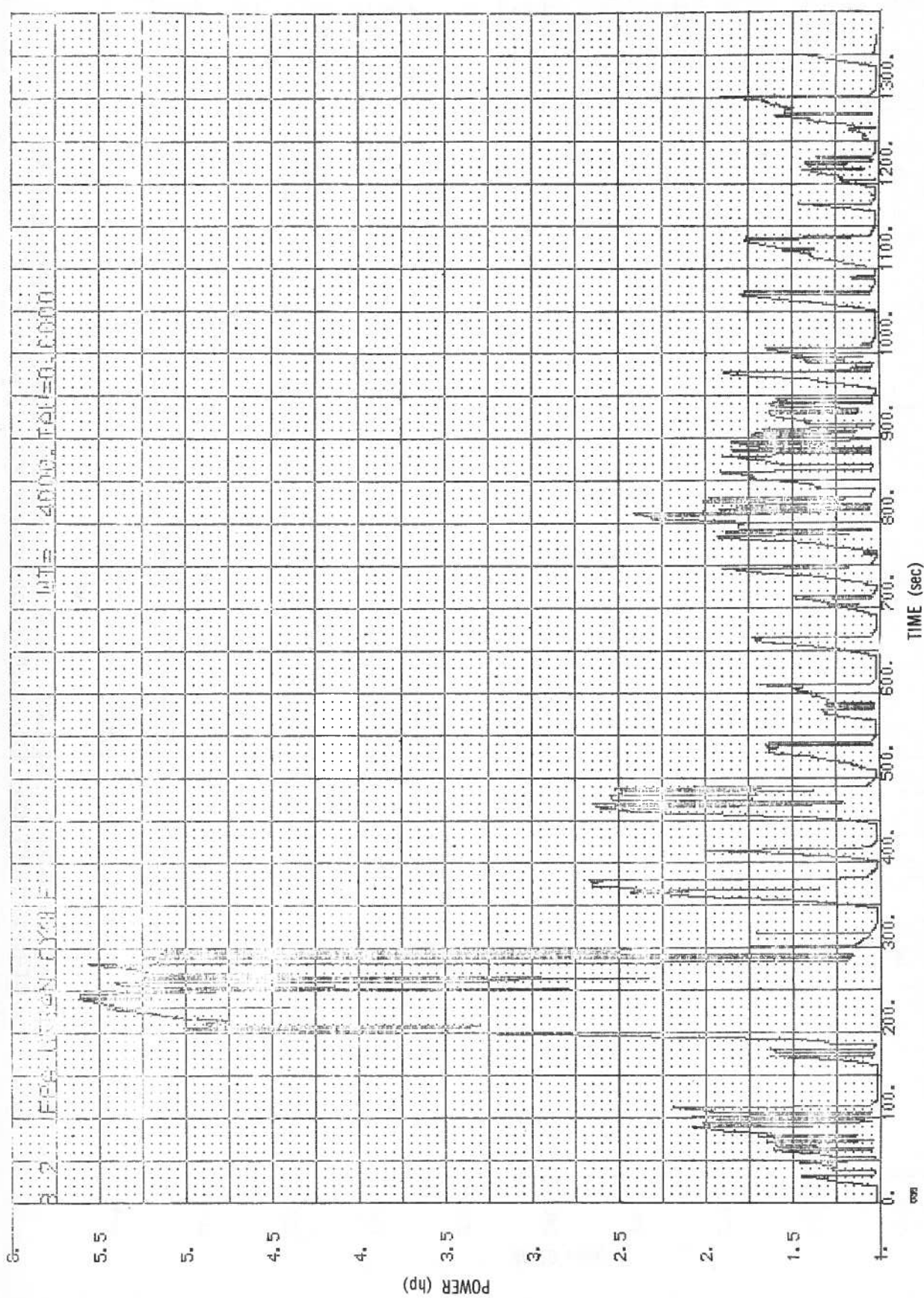


FIGURE 10-7. ACCESSORY POWER DEMAND HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0$

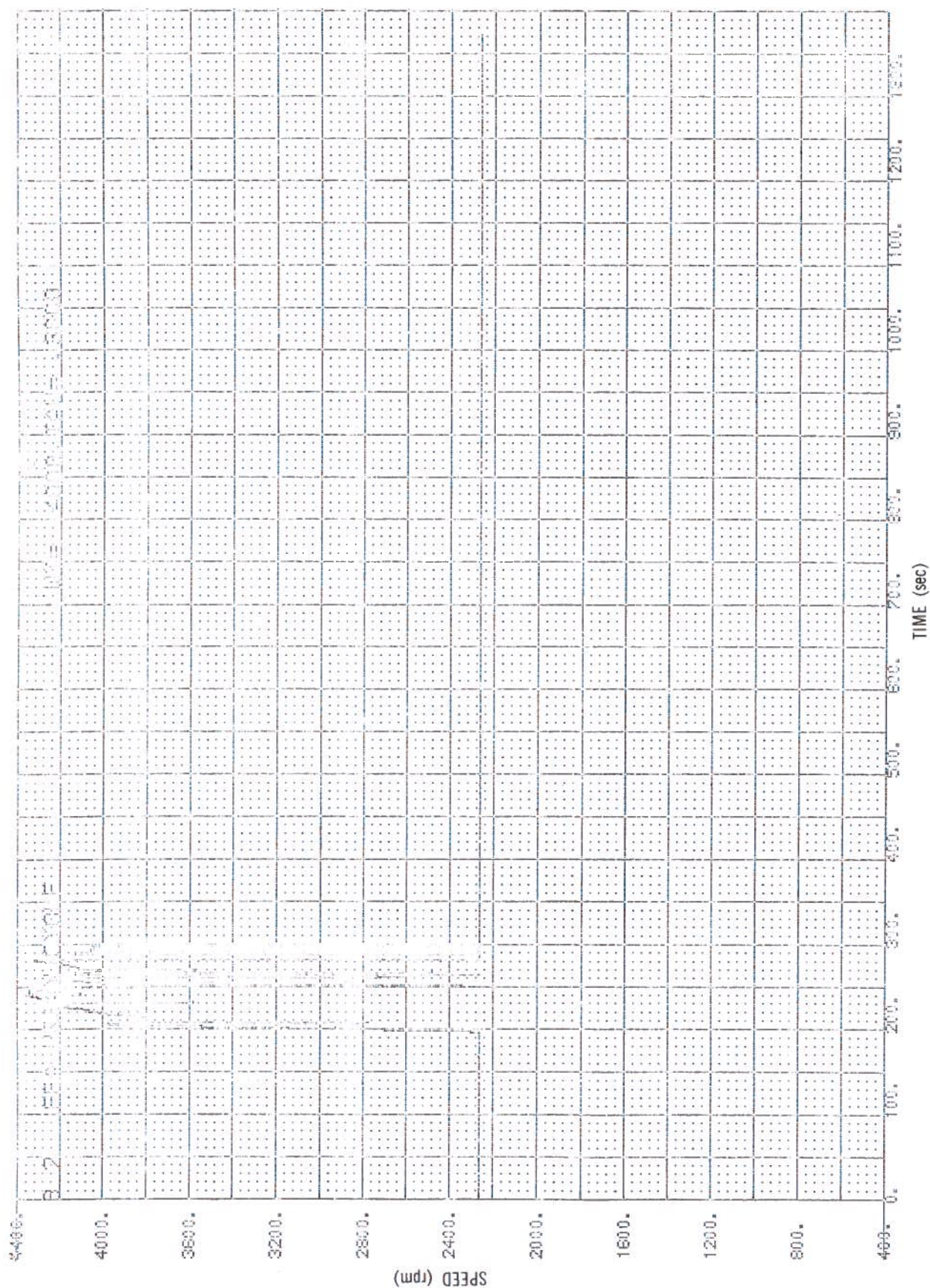


FIGURE 10-8. ENGINE SPEED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

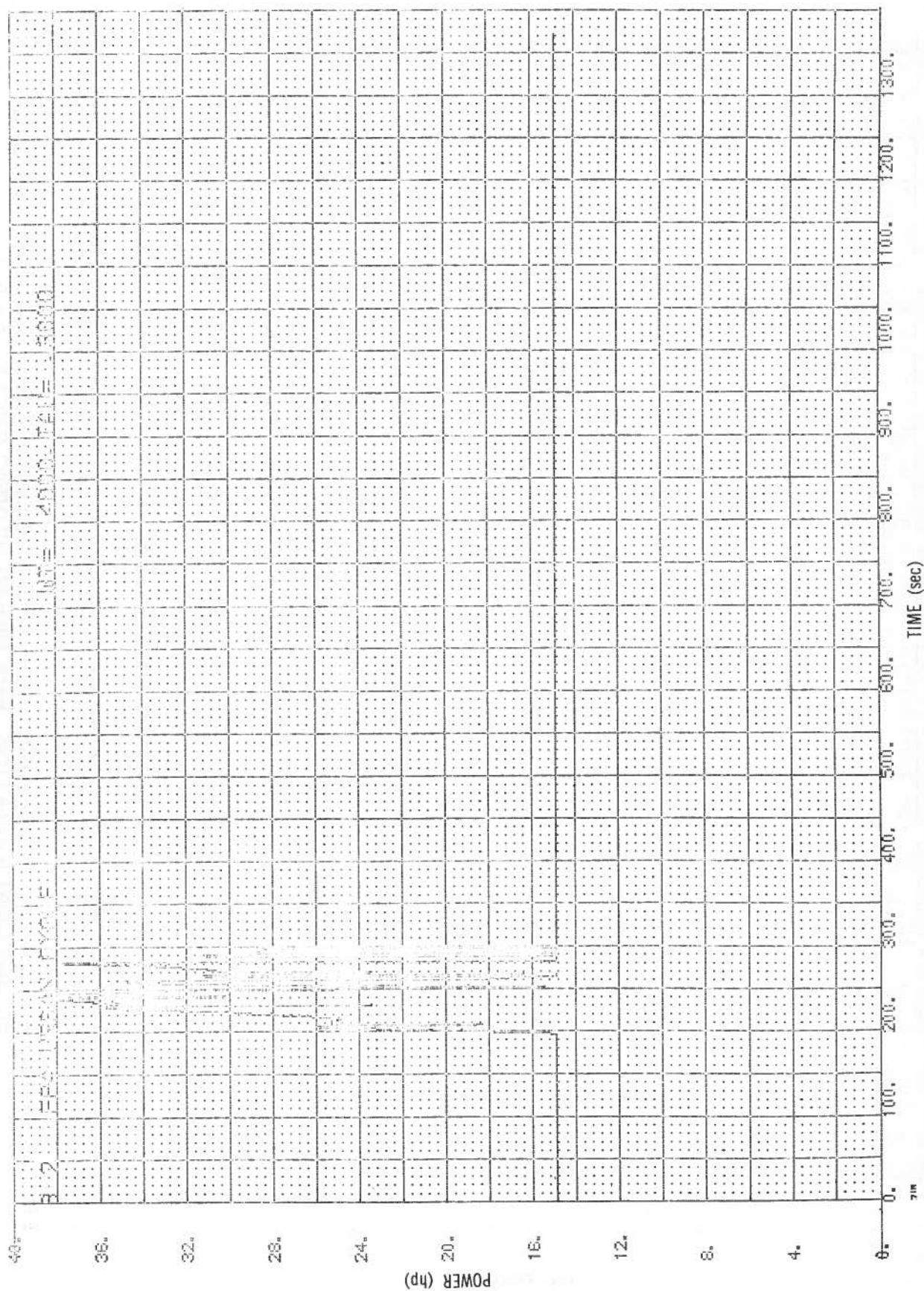


FIGURE 10-9. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

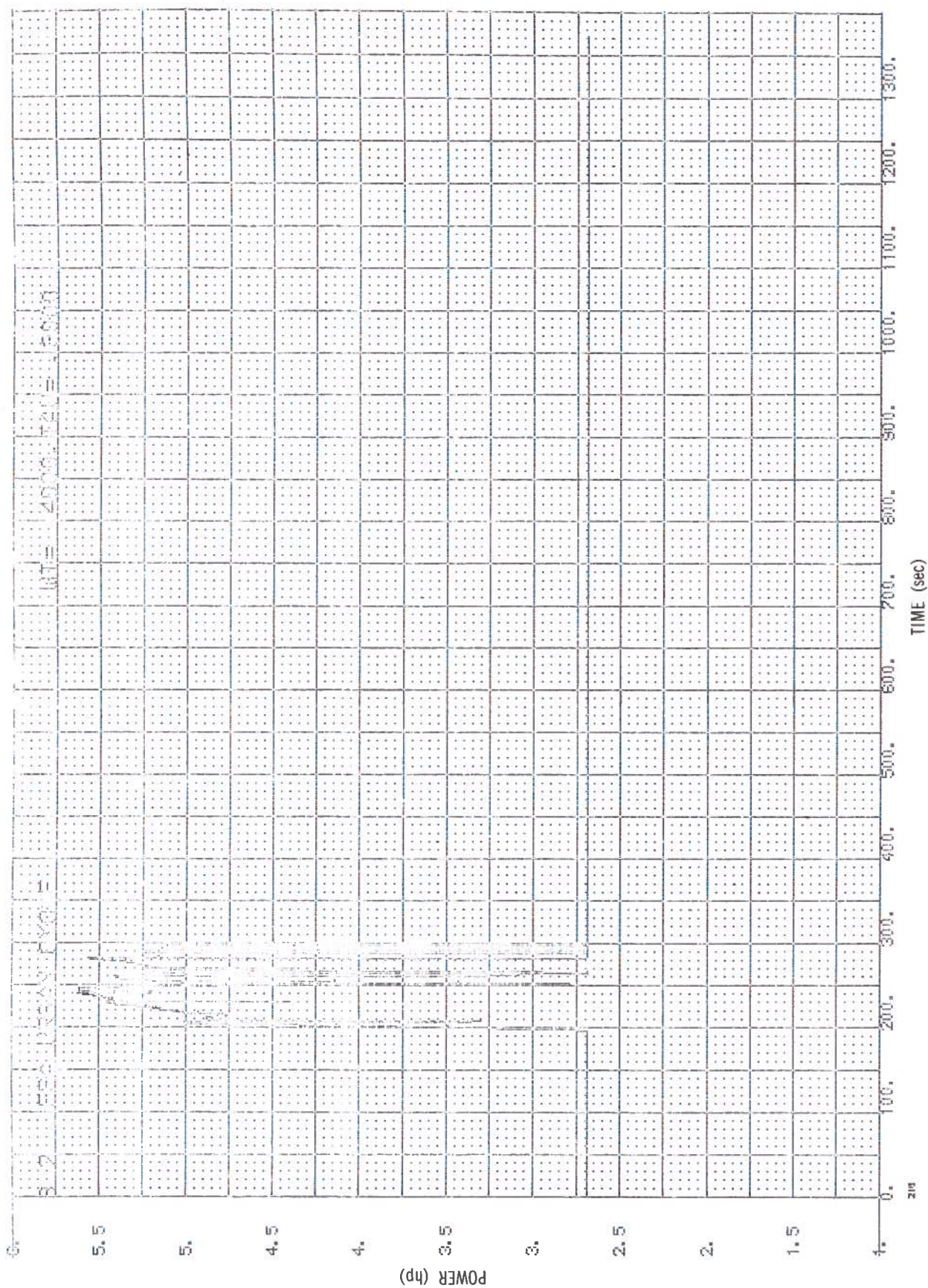


FIGURE 10-10. ACCESSORY POWER DEMAND HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

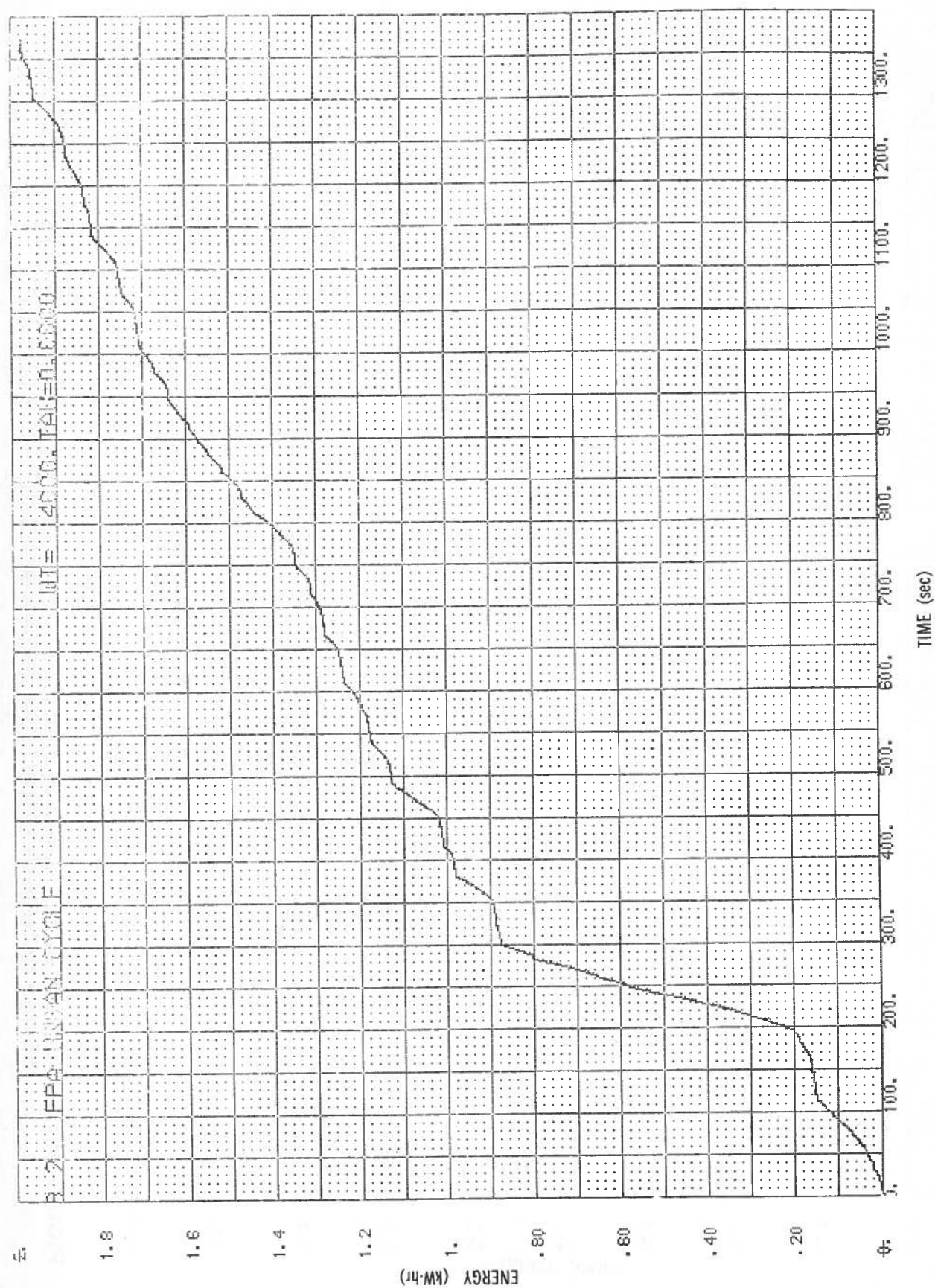


FIGURE 10-11. ENGINE SHAFT ENERGY PROVIDED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0$

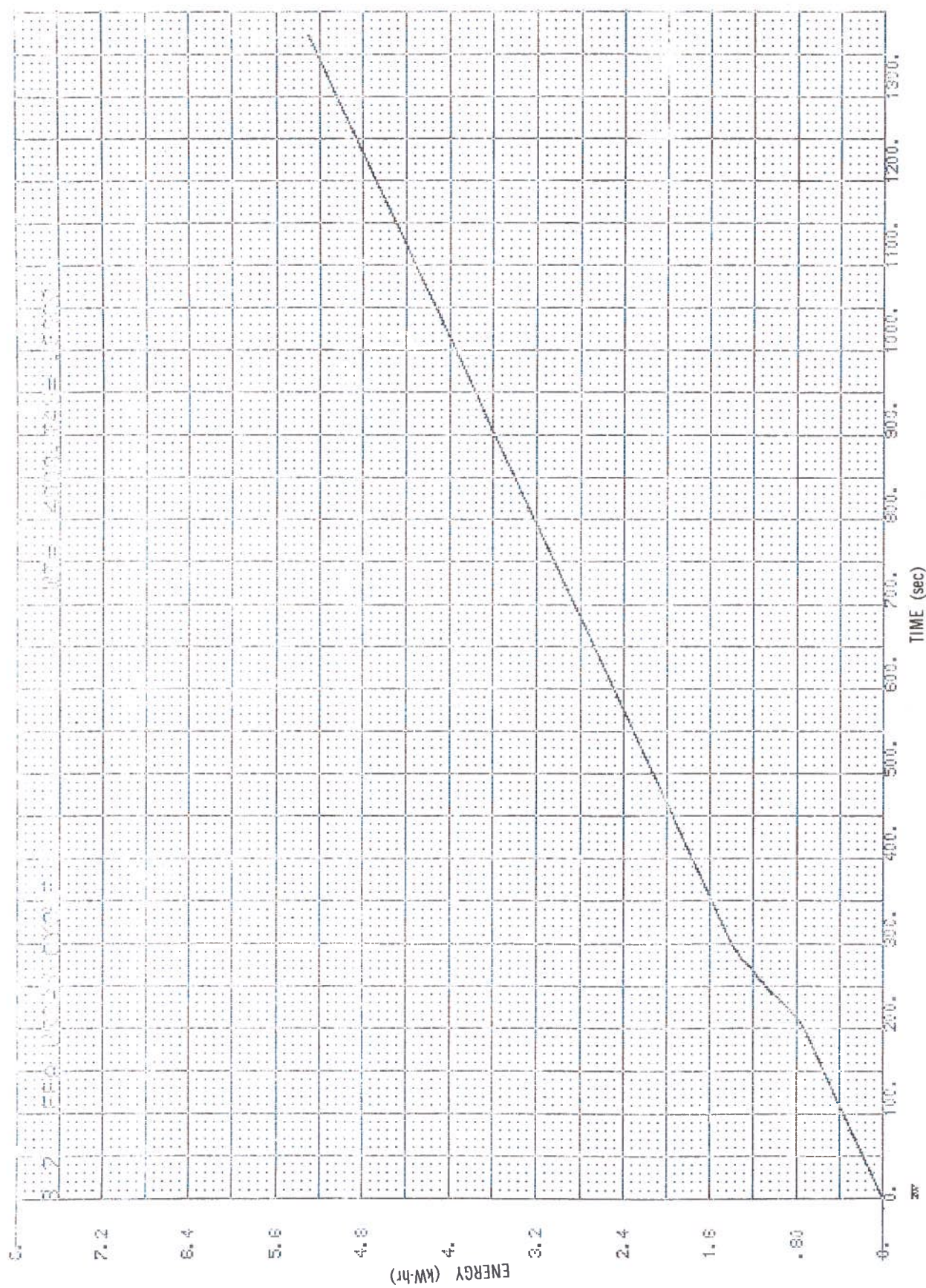


FIGURE 10-12. ENGINE SHAFT ENERGY PROVIDED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

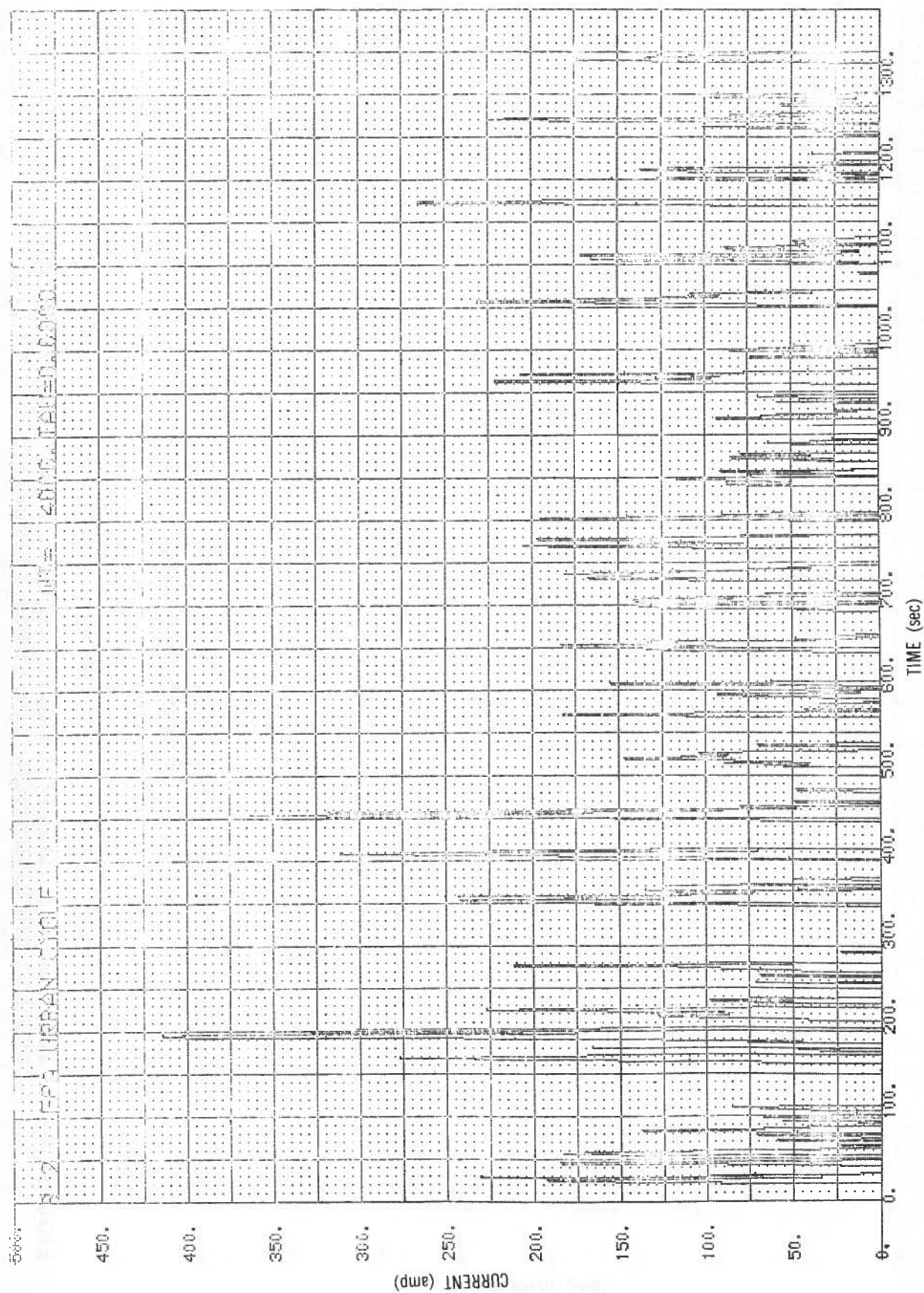


FIGURE 10-13. BATTERY DISCHARGE CURRENT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0$

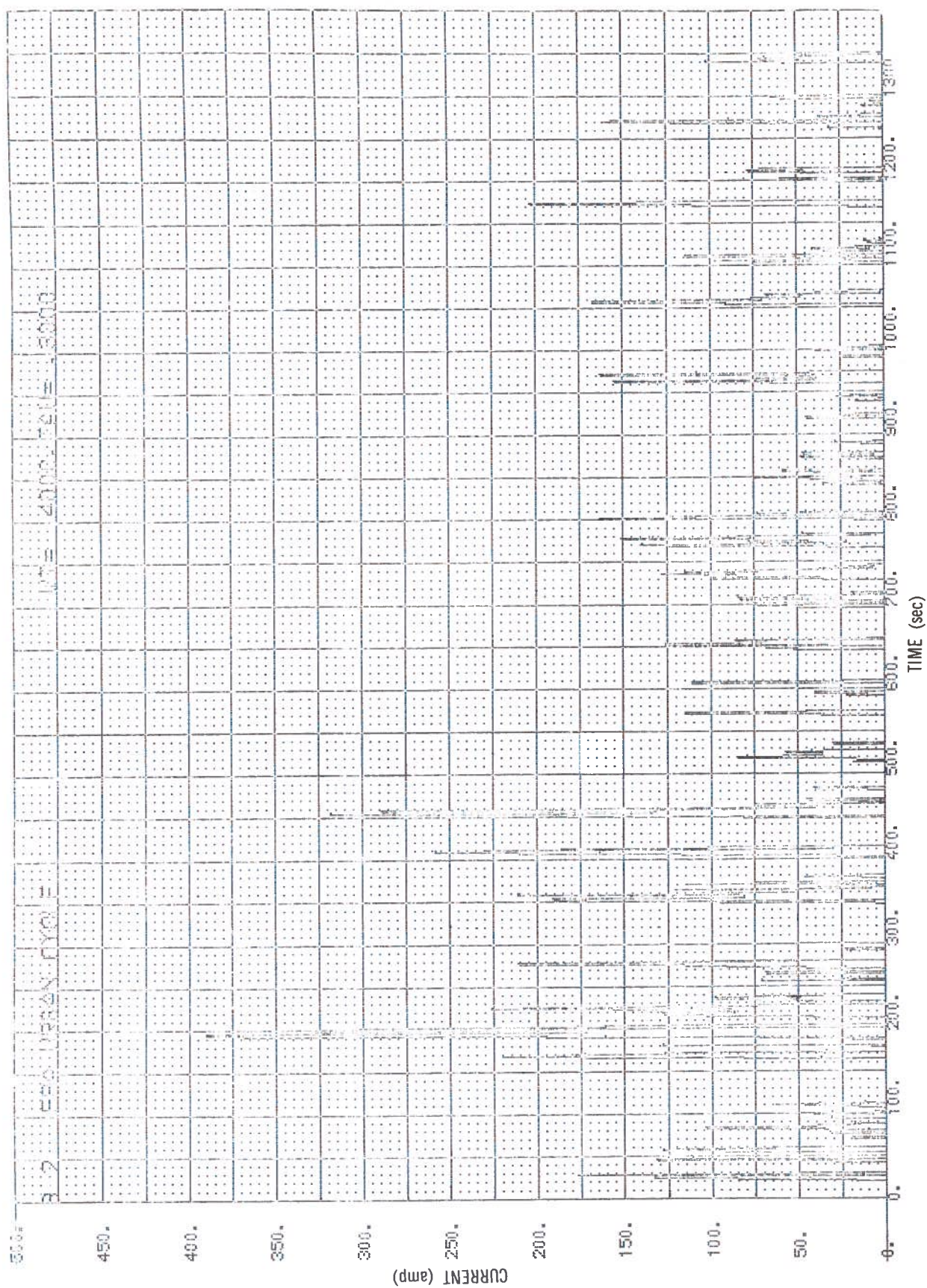


FIGURE 10-14. BATTERY DISCHARGE CURRENT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

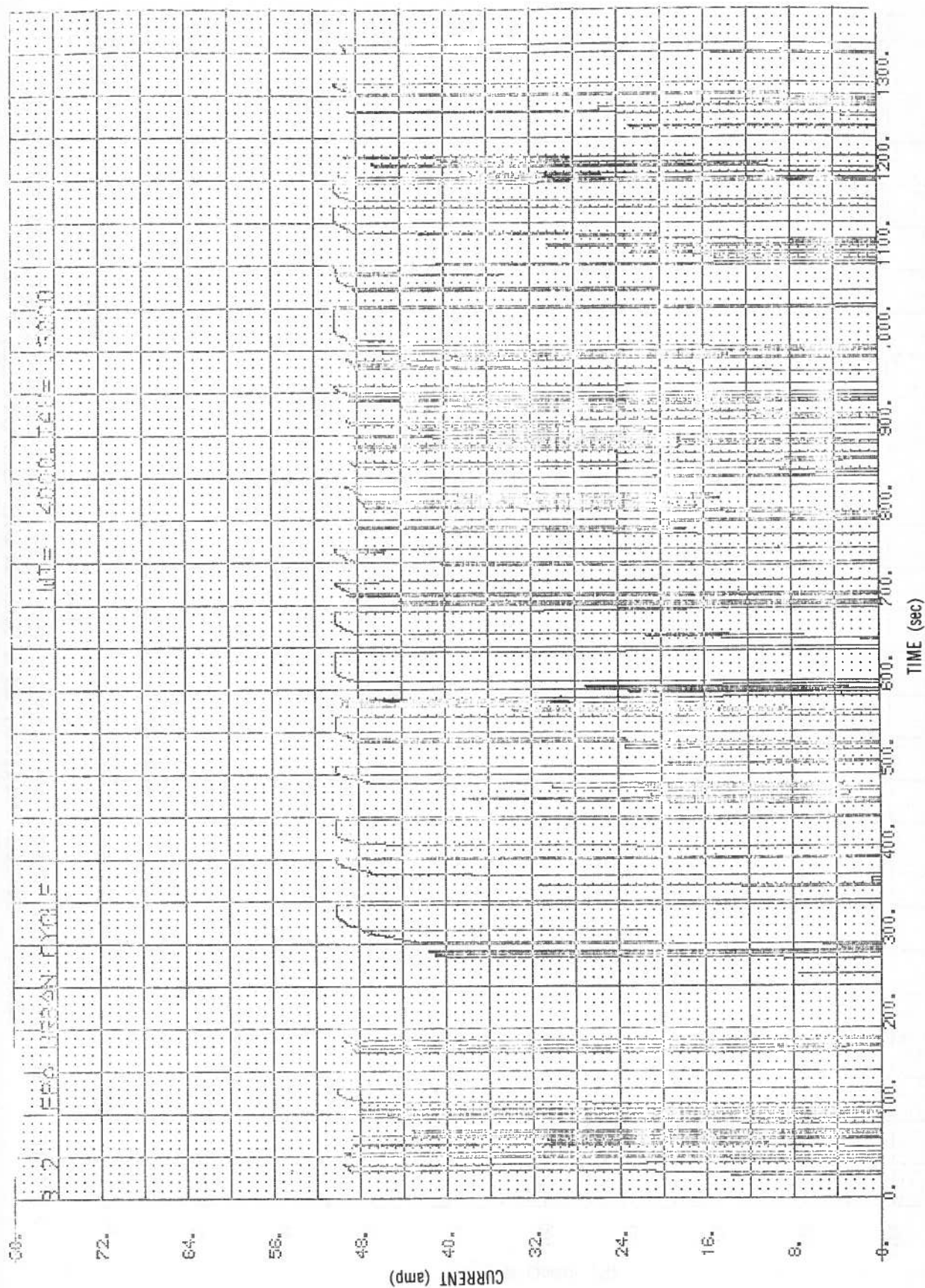


FIGURE 10-15. BATTERY CHARGE CURRENT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

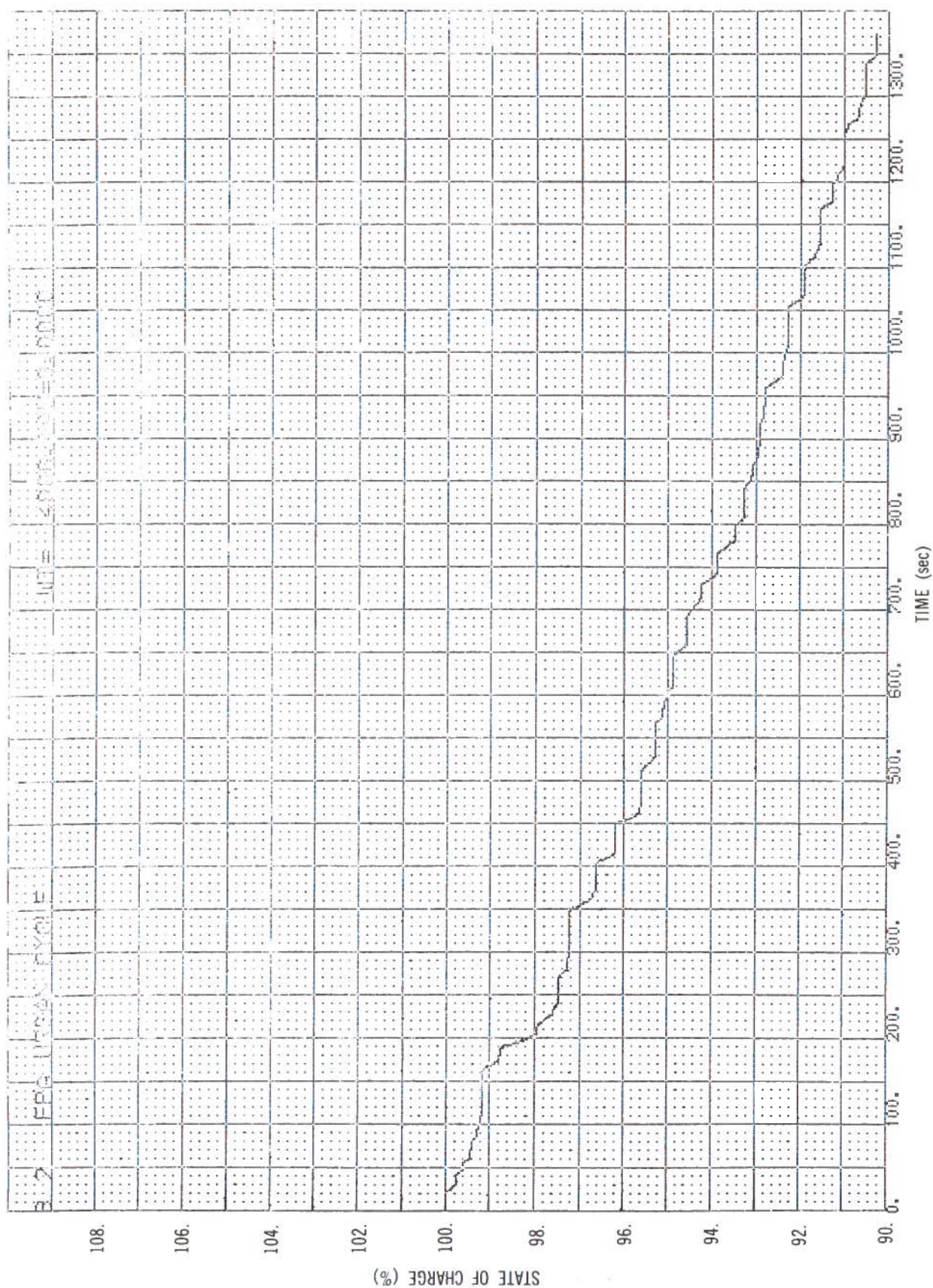


FIGURE 10-16. BATTERY STATE OF CHARGE HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0$

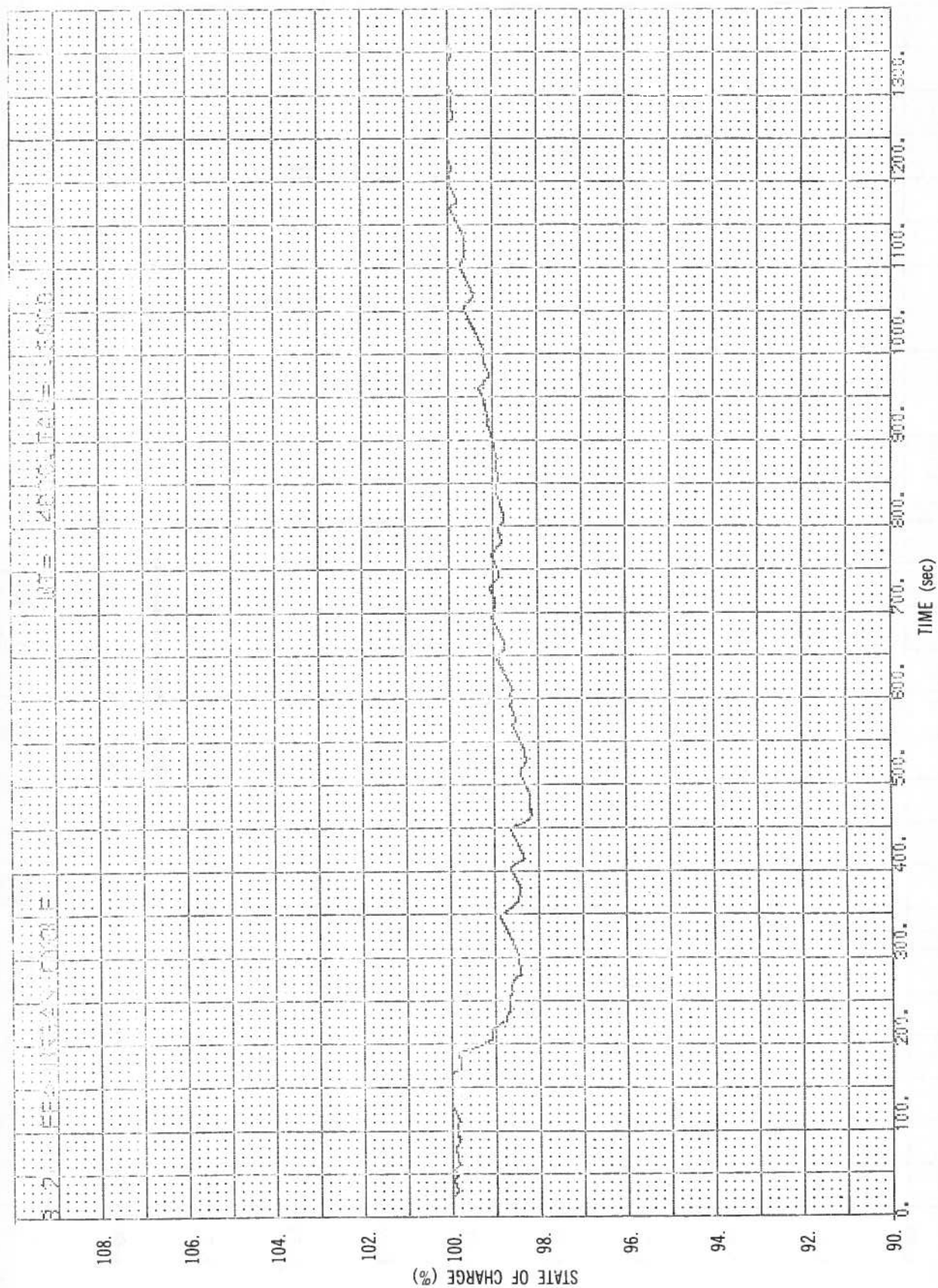


FIGURE 10-17. BATTERY STATE OF CHARGE HISTORY: HEAT ENGINE/BATTERY SYSTEM,
SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

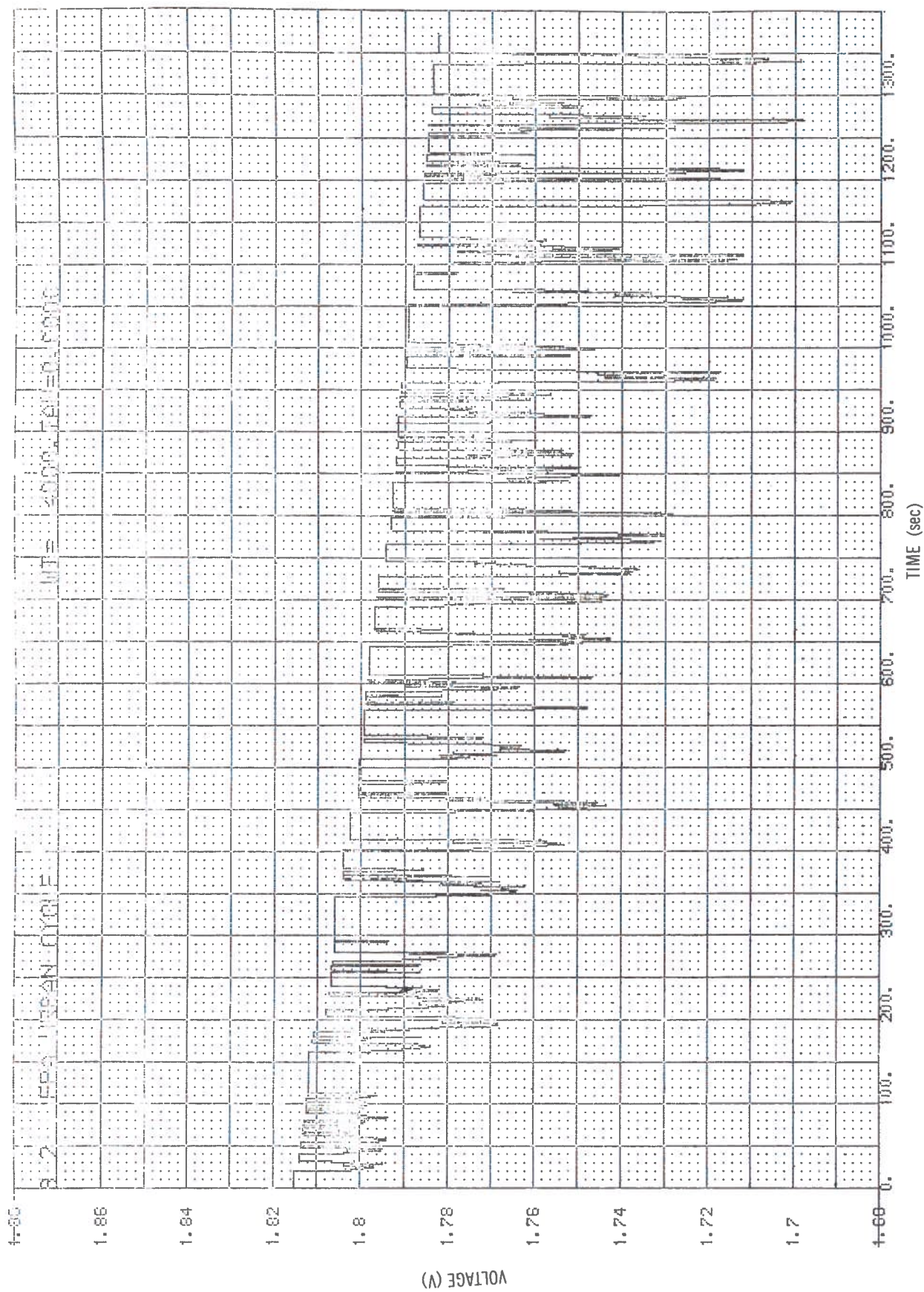


FIGURE 10-18. BATTERY CELL VOLTAGE HISTORY: HEAT ENGINE/BATTERY SYSTEM,
SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0$

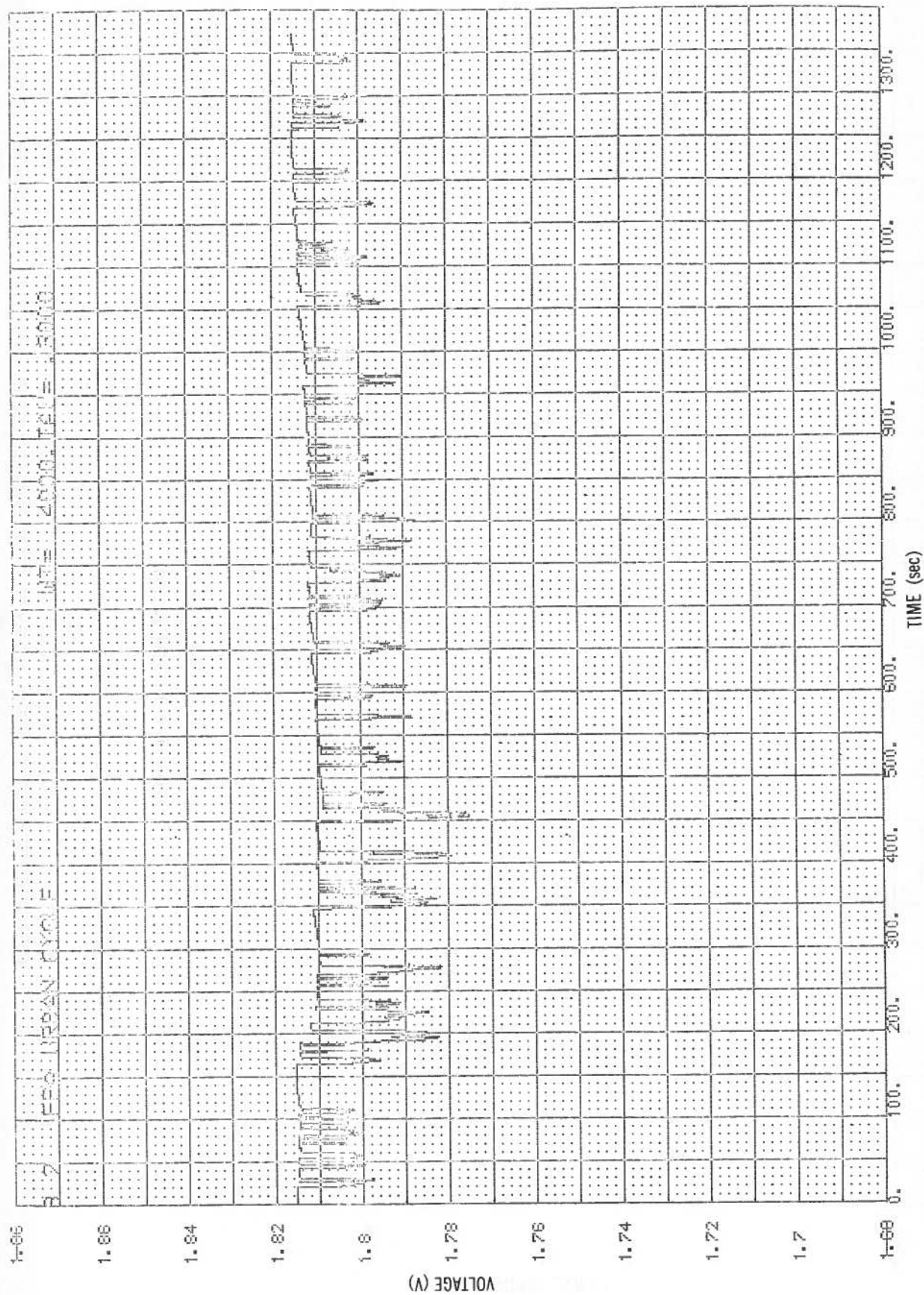


FIGURE 10-19. BATTERY CELL VOLTAGE HISTORY: HEAT ENGINE/BATTERY SYSTEM,
SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

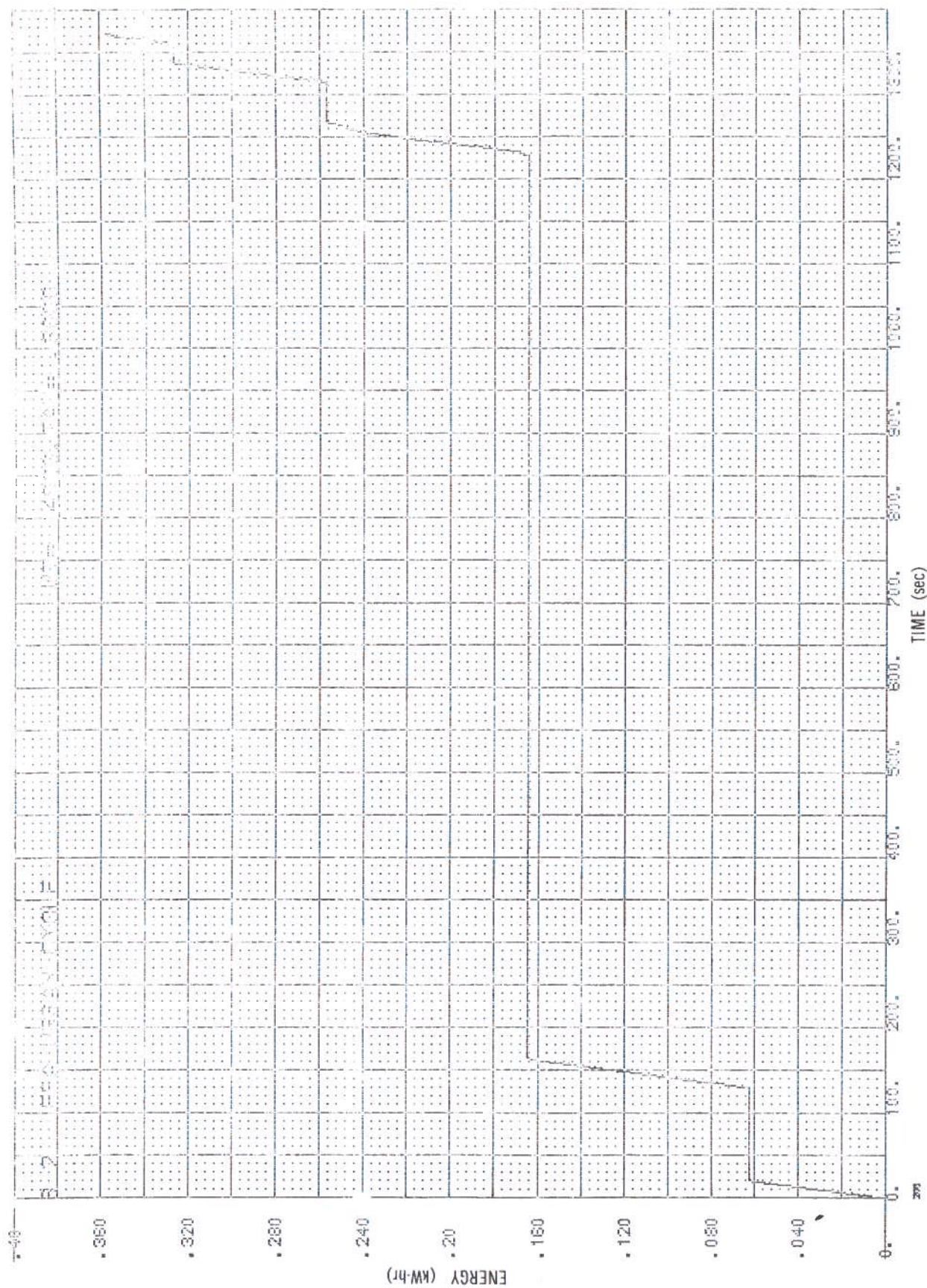


FIGURE 10-20. WASTED ENERGY HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.3$

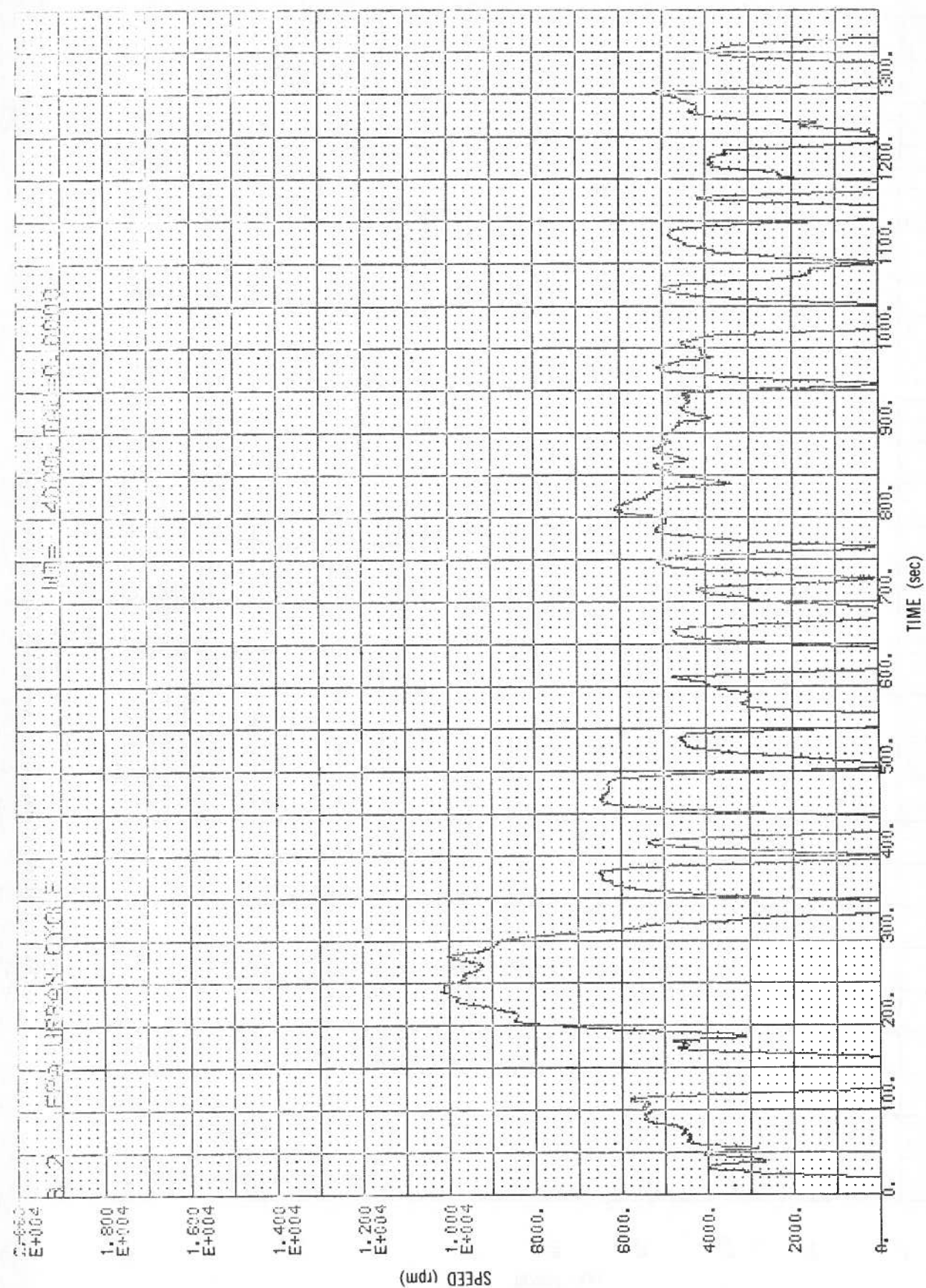


FIGURE 10-21. MOTOR SPEED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

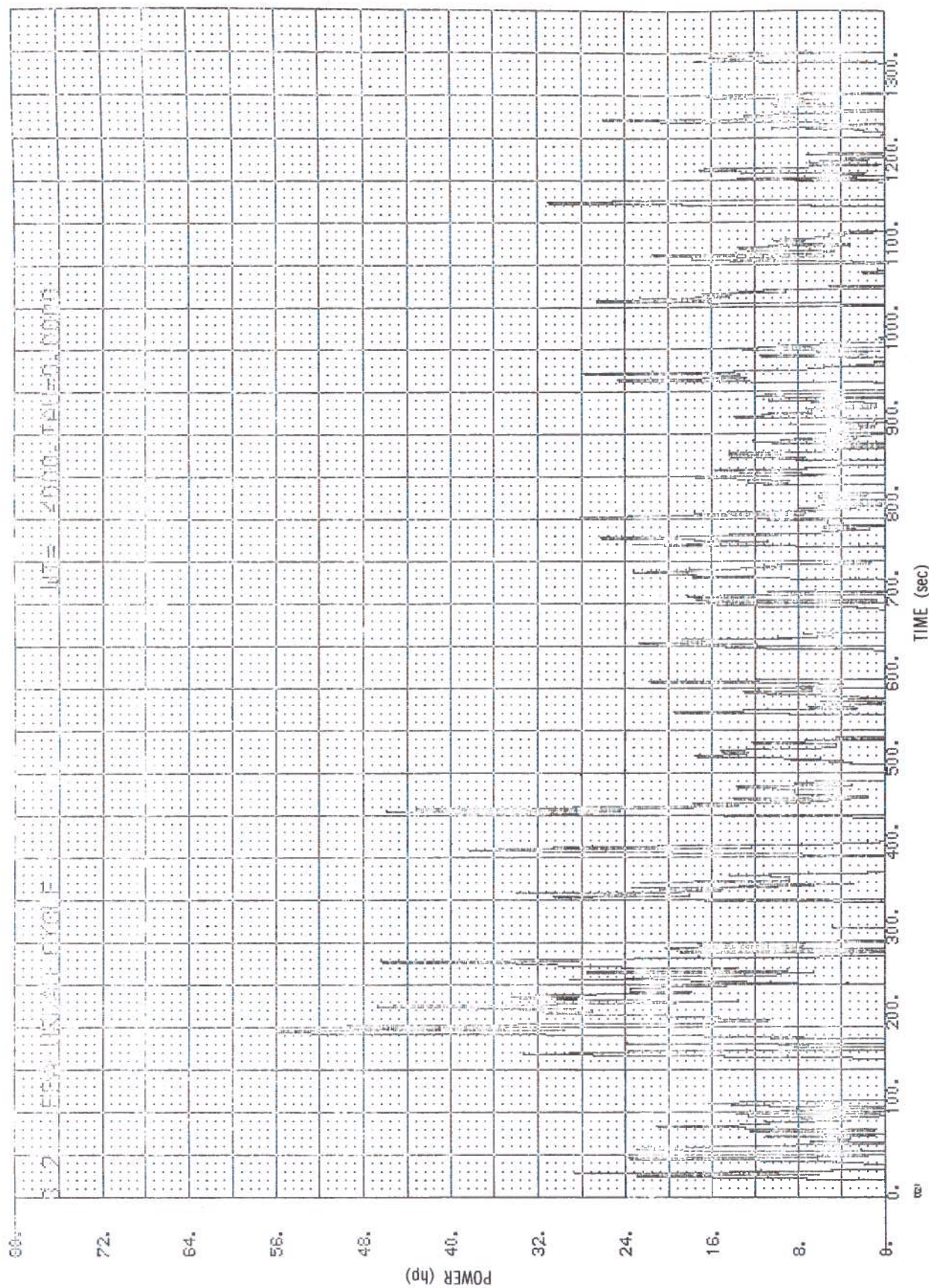


FIGURE 10-22. MOTOR POWER HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

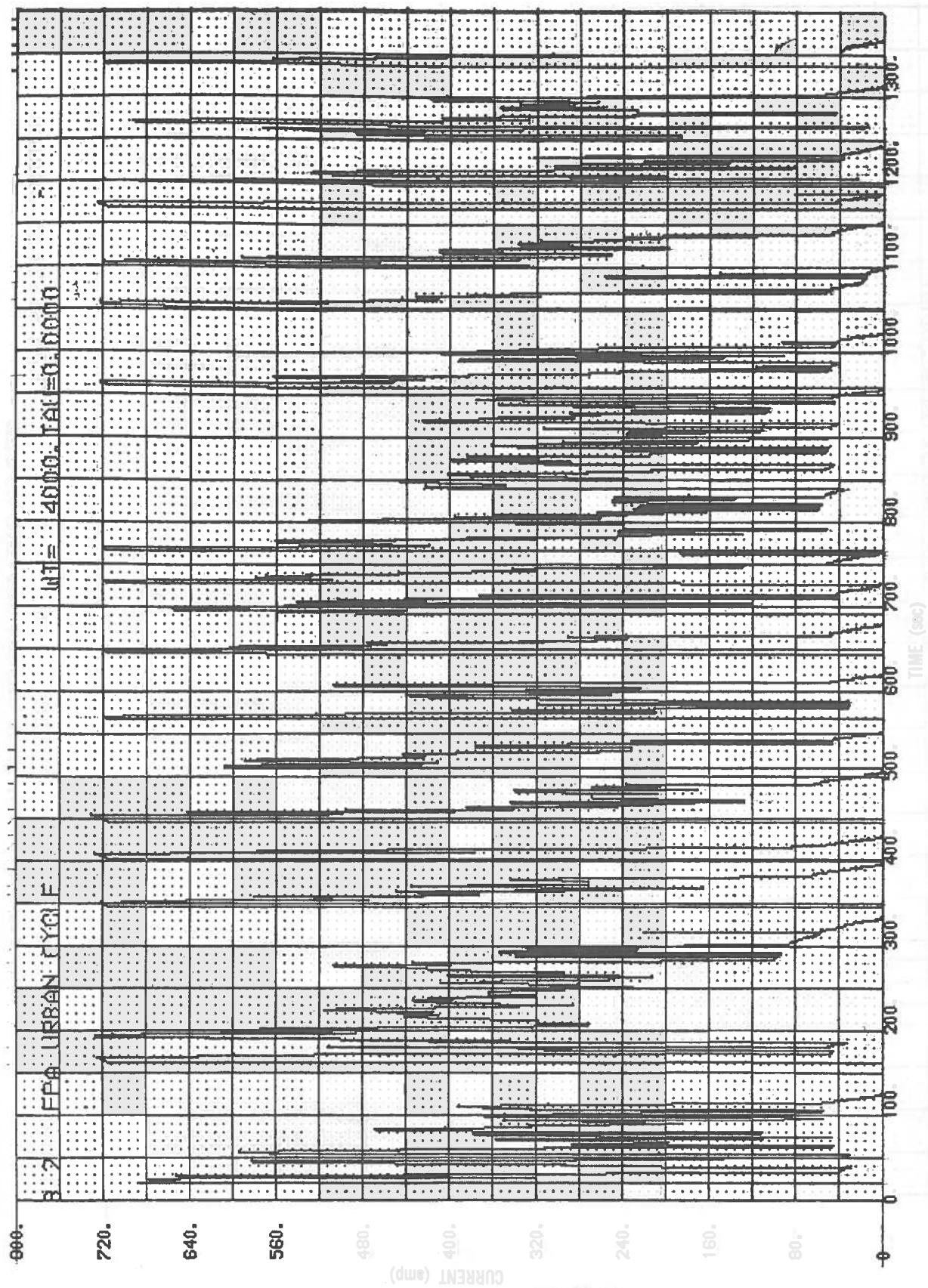


FIGURE 10-23. MOTOR CURRENT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

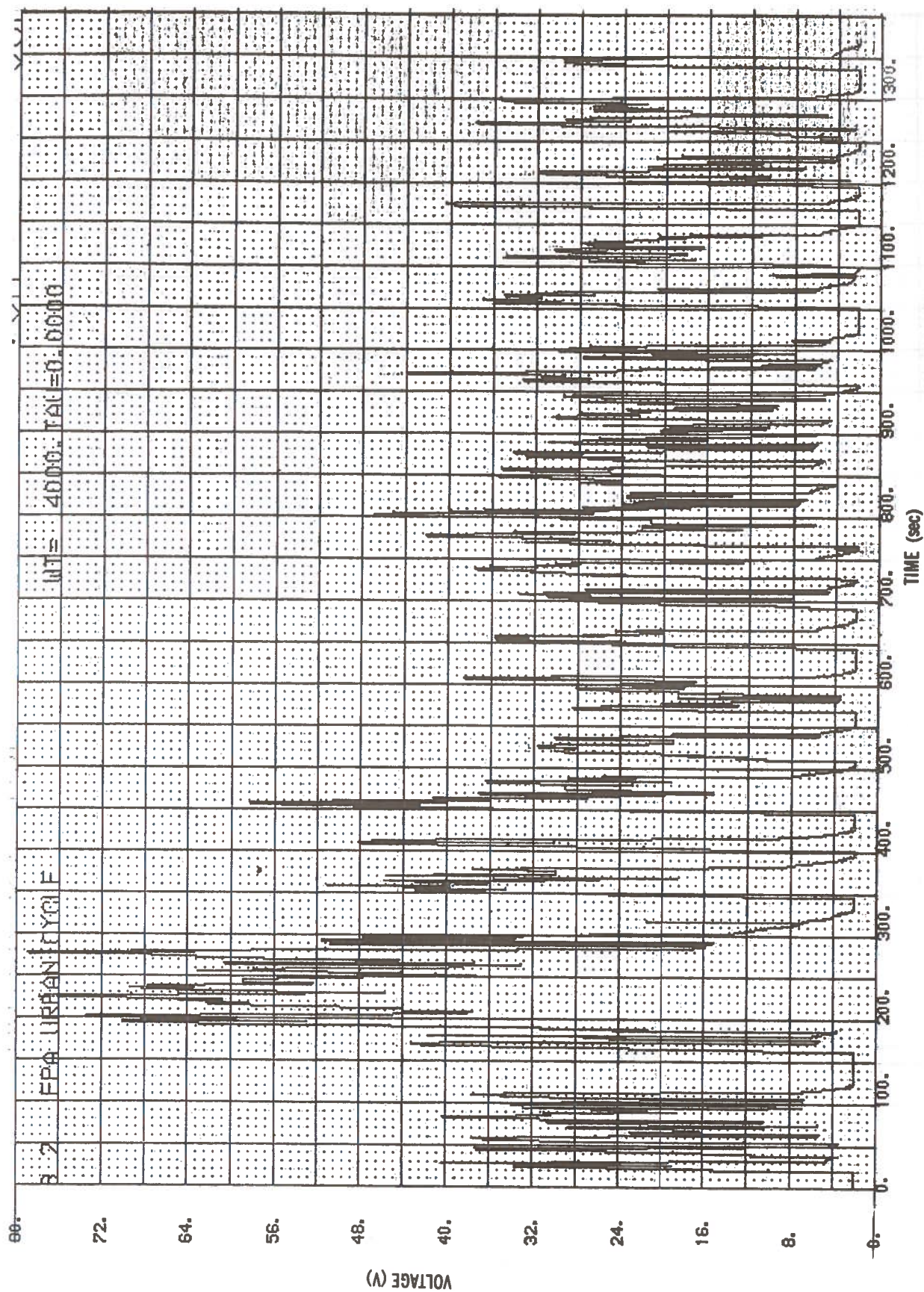


FIGURE 10-24. MOTOR VOLTAGE HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

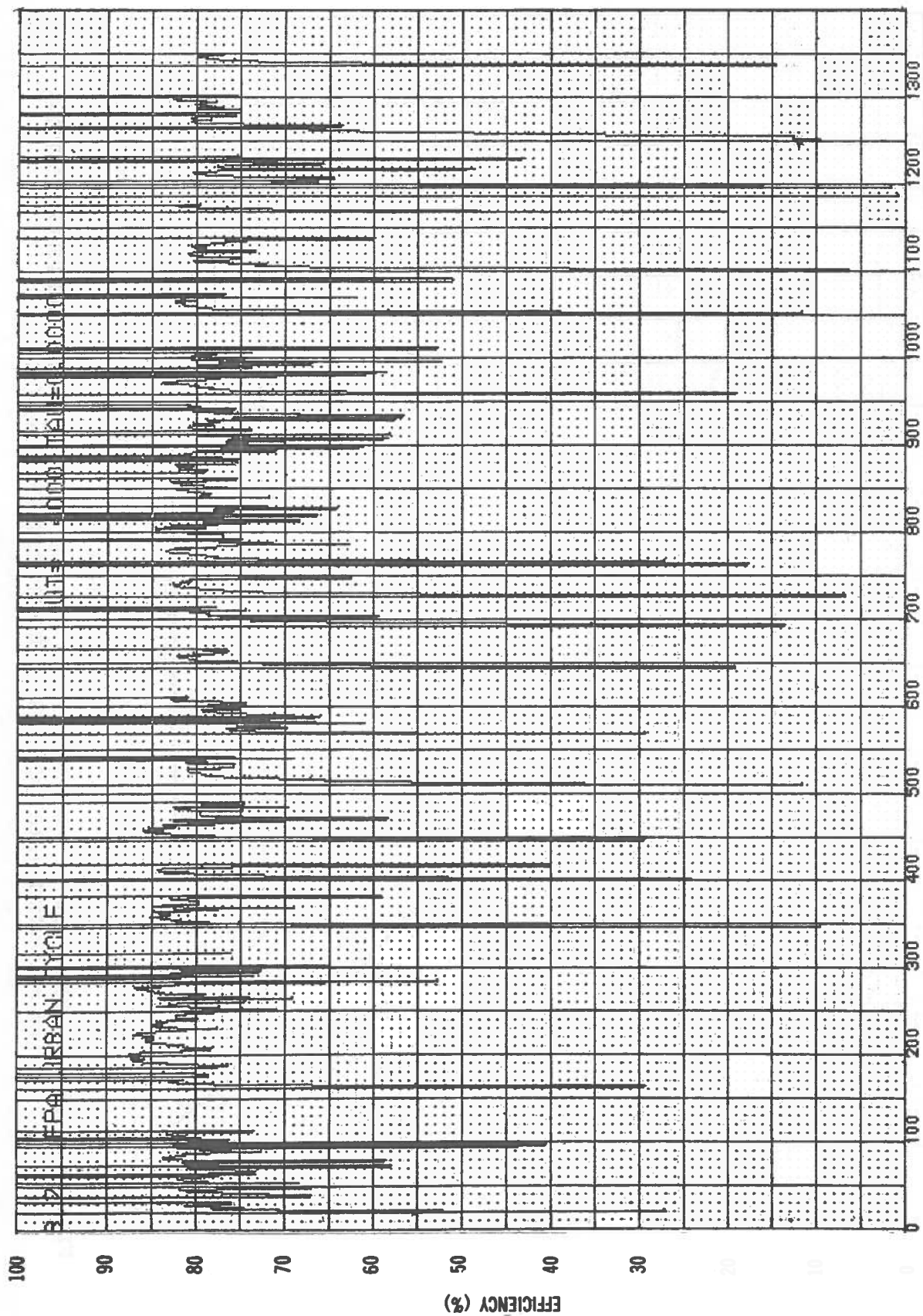


FIGURE 10-25-4. HIGH-INTENSITY SIGNAL VARIATION IN URBAN SYSTEM, SERIES 1. CONFINED TO ONE LANE AND ONE CYCLE.

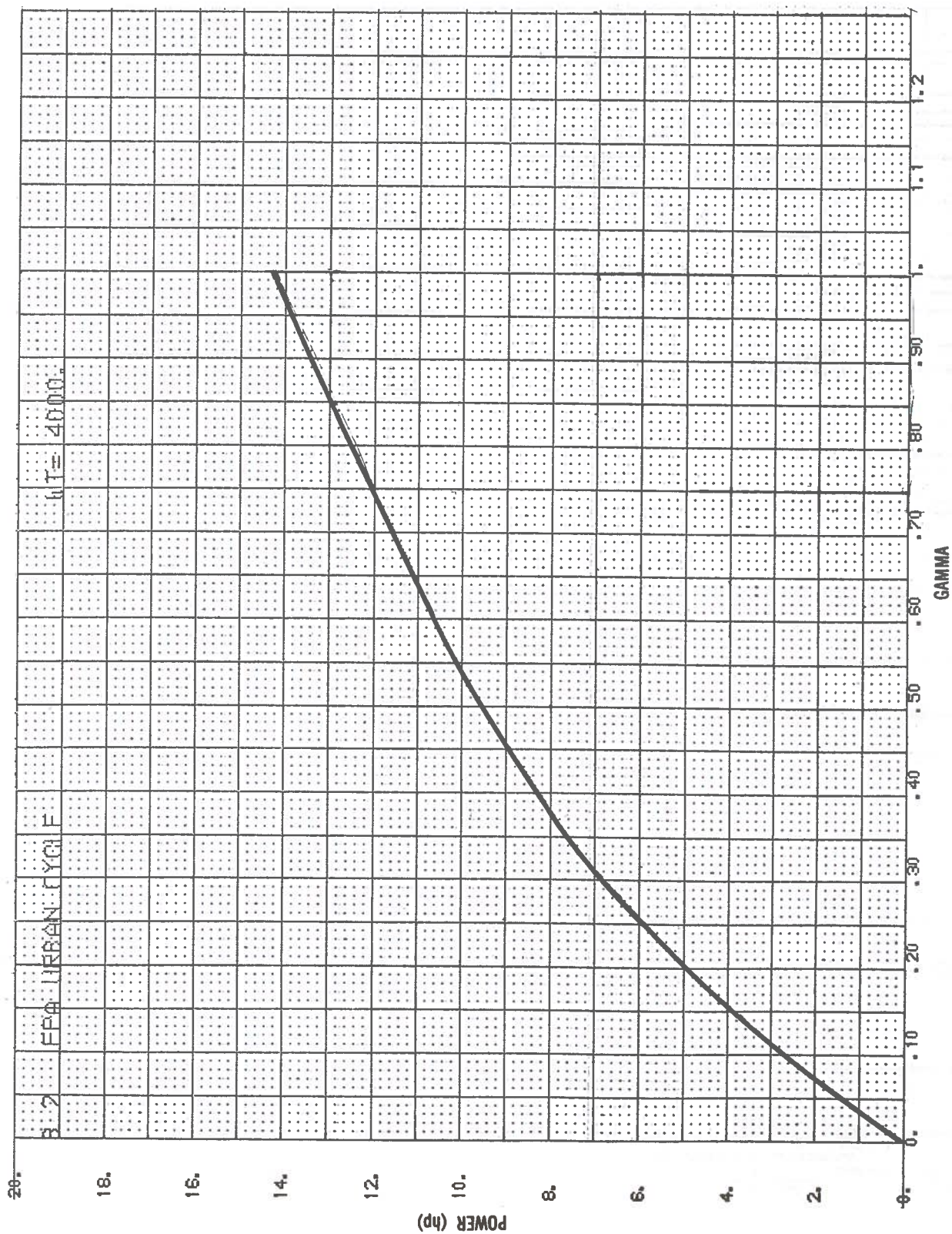


FIGURE 10-26. ENGINE POWER USED FOR PROPULSION: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

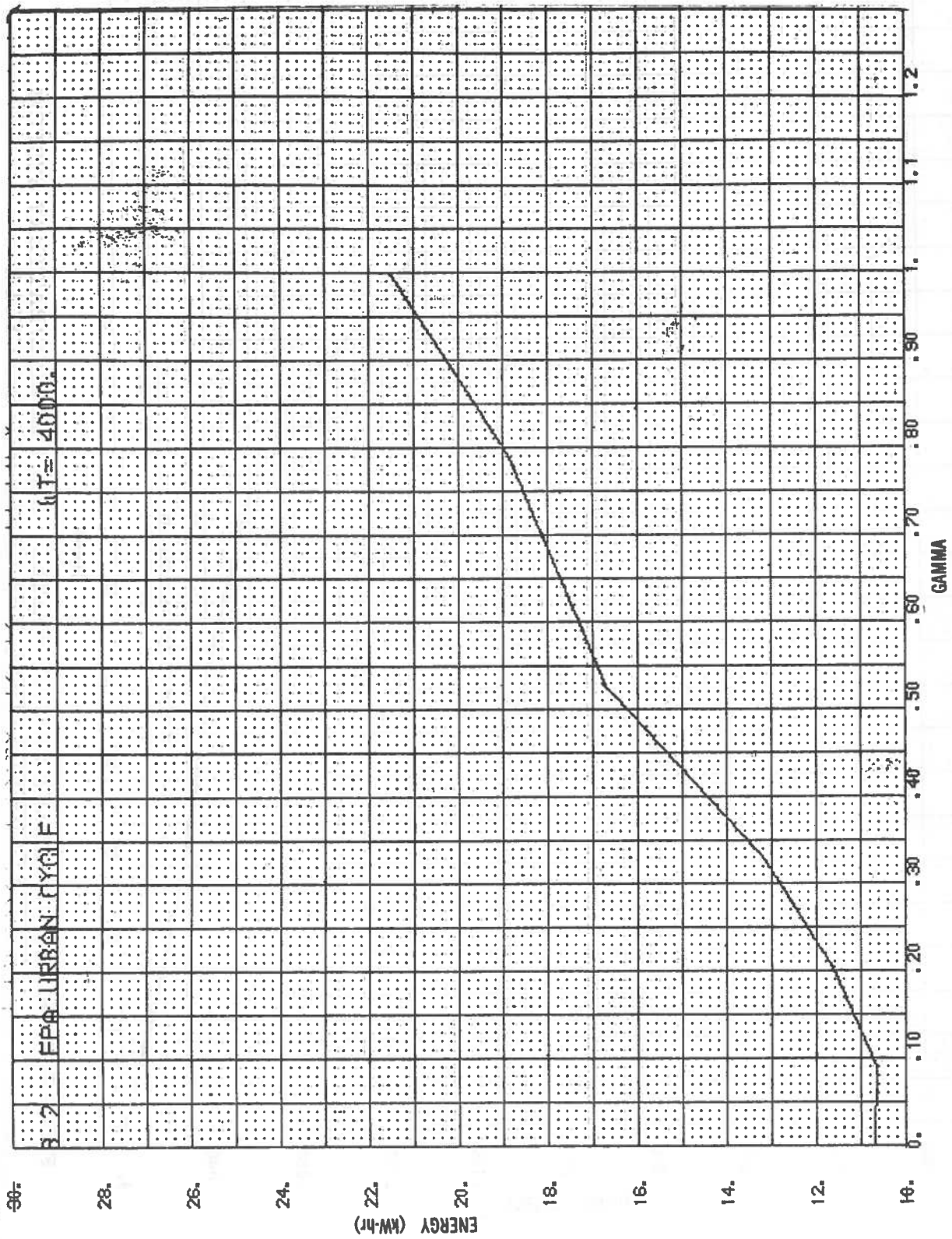


FIGURE 10-27. ENGINE FUEL ENERGY PROVIDED: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

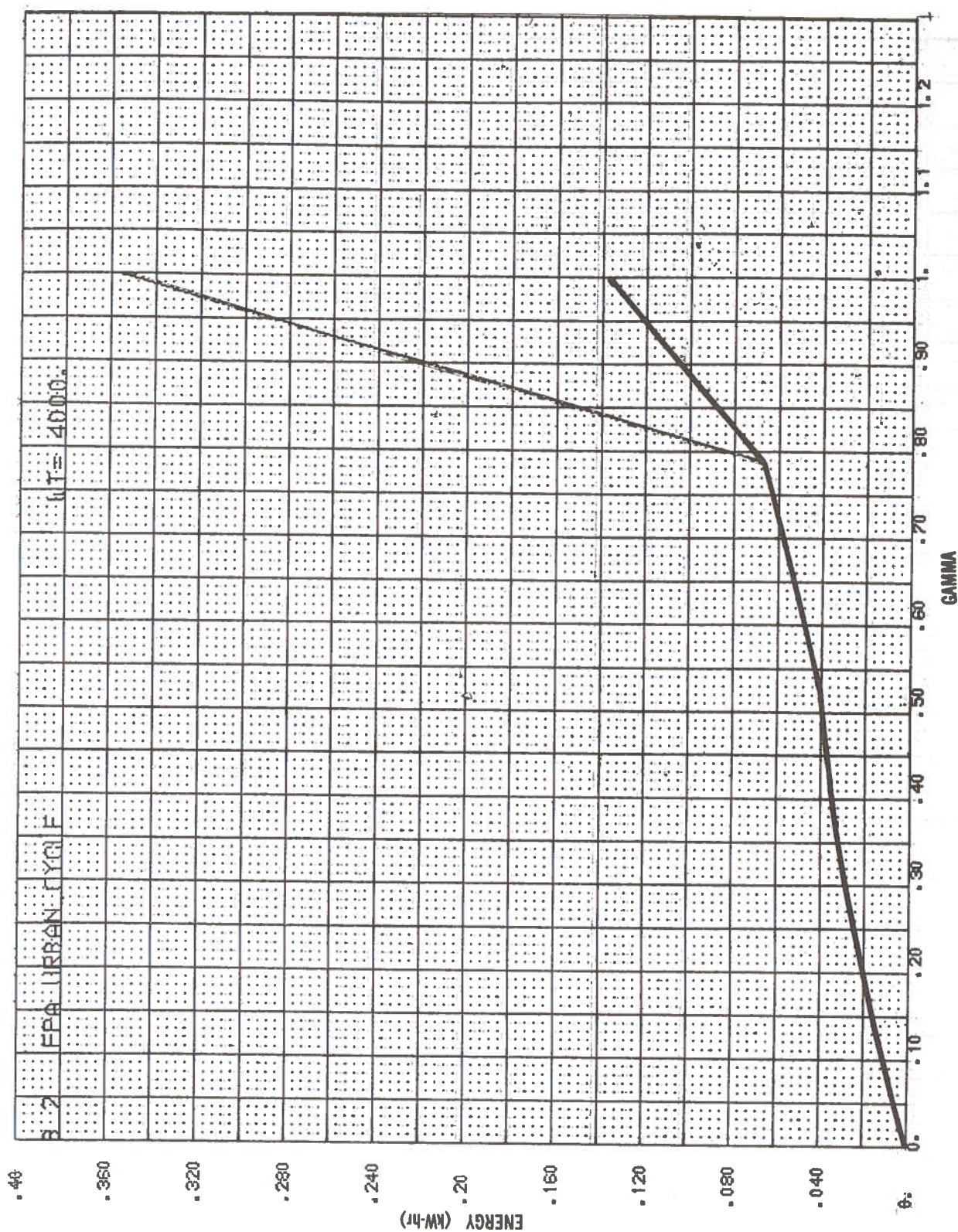


FIGURE 10-28. ENGINE SHAFT ENERGY WASTED: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

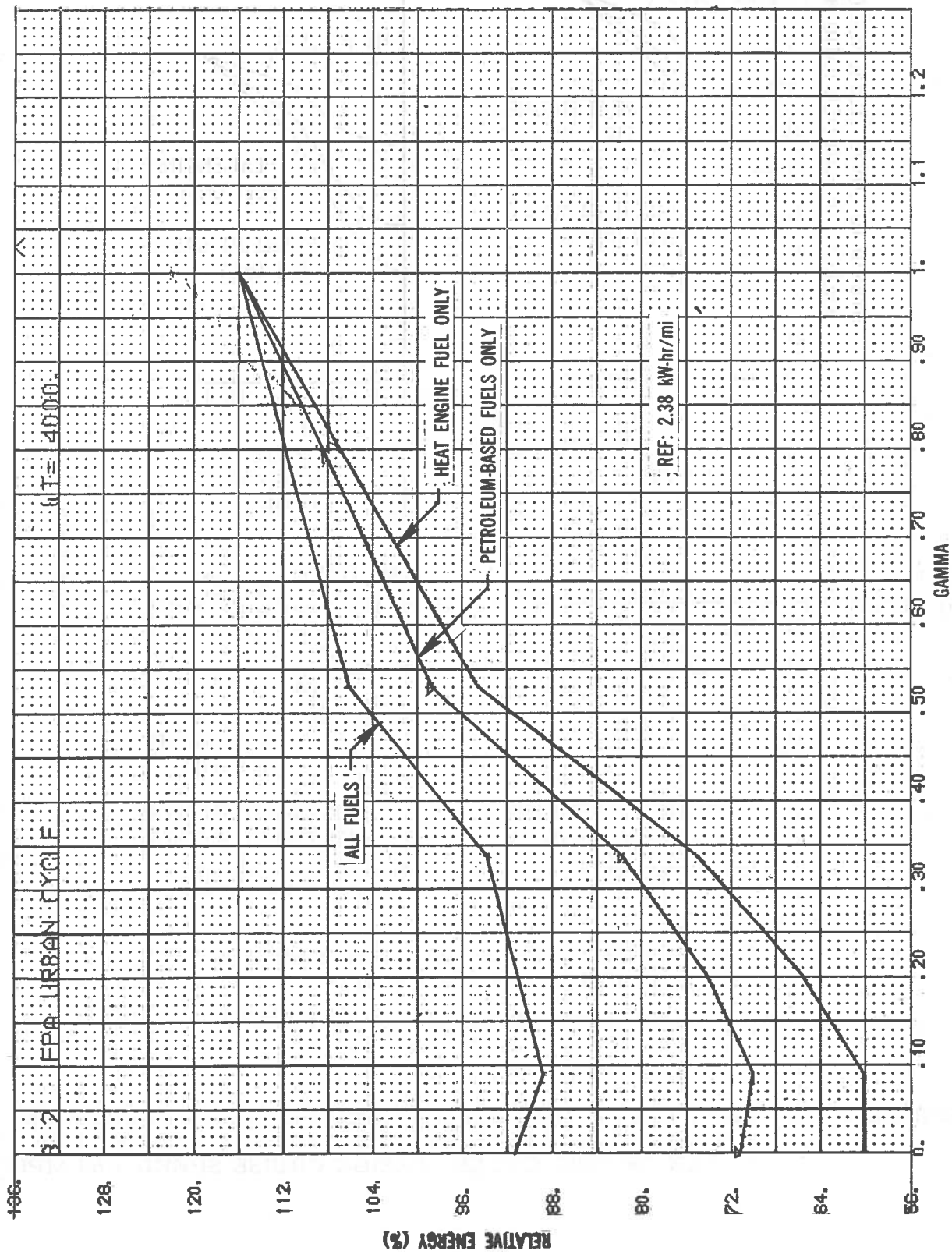


FIGURE 10-29. FUEL ENERGY CONSUMPTION: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

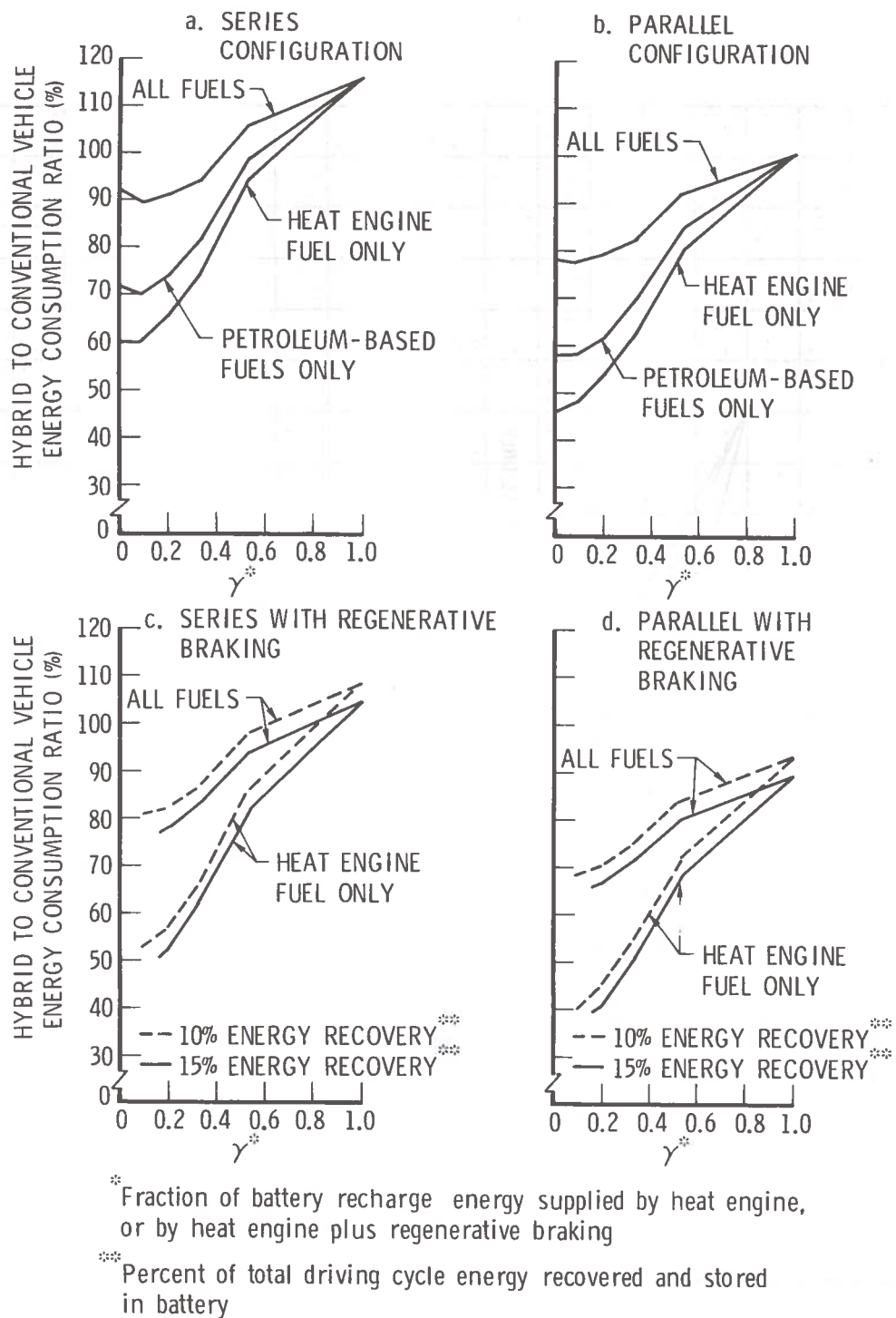
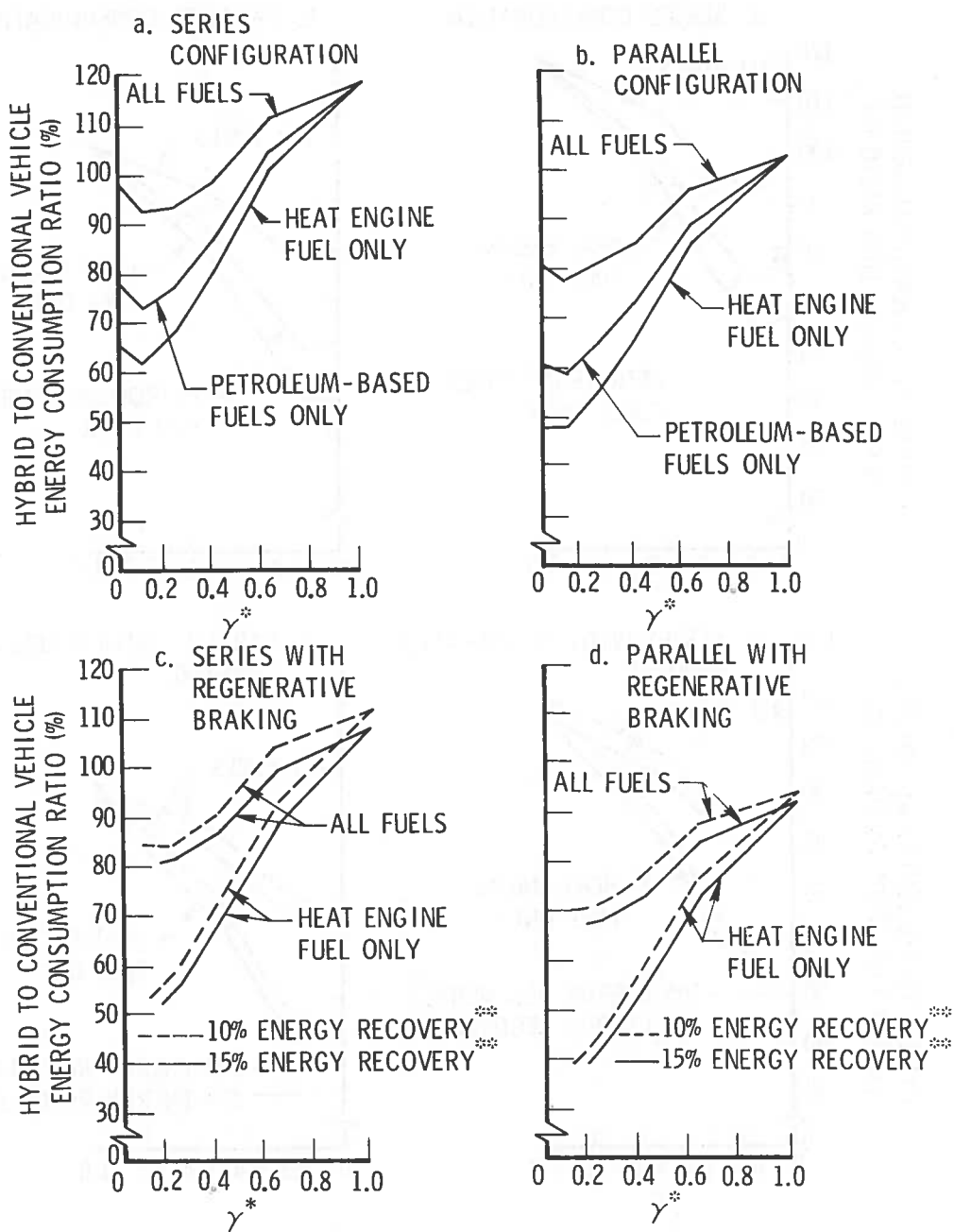


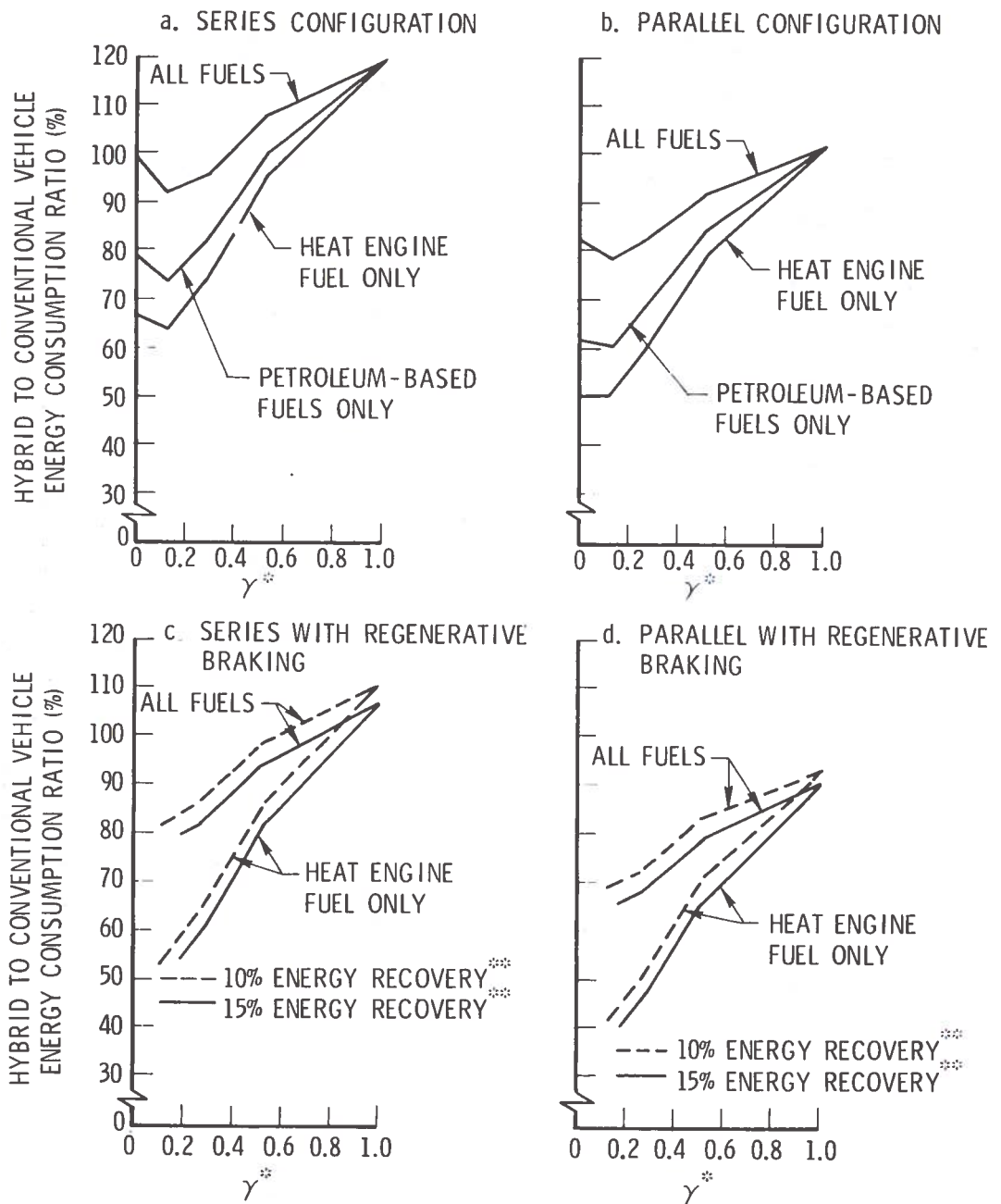
FIGURE 10-30. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



* 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

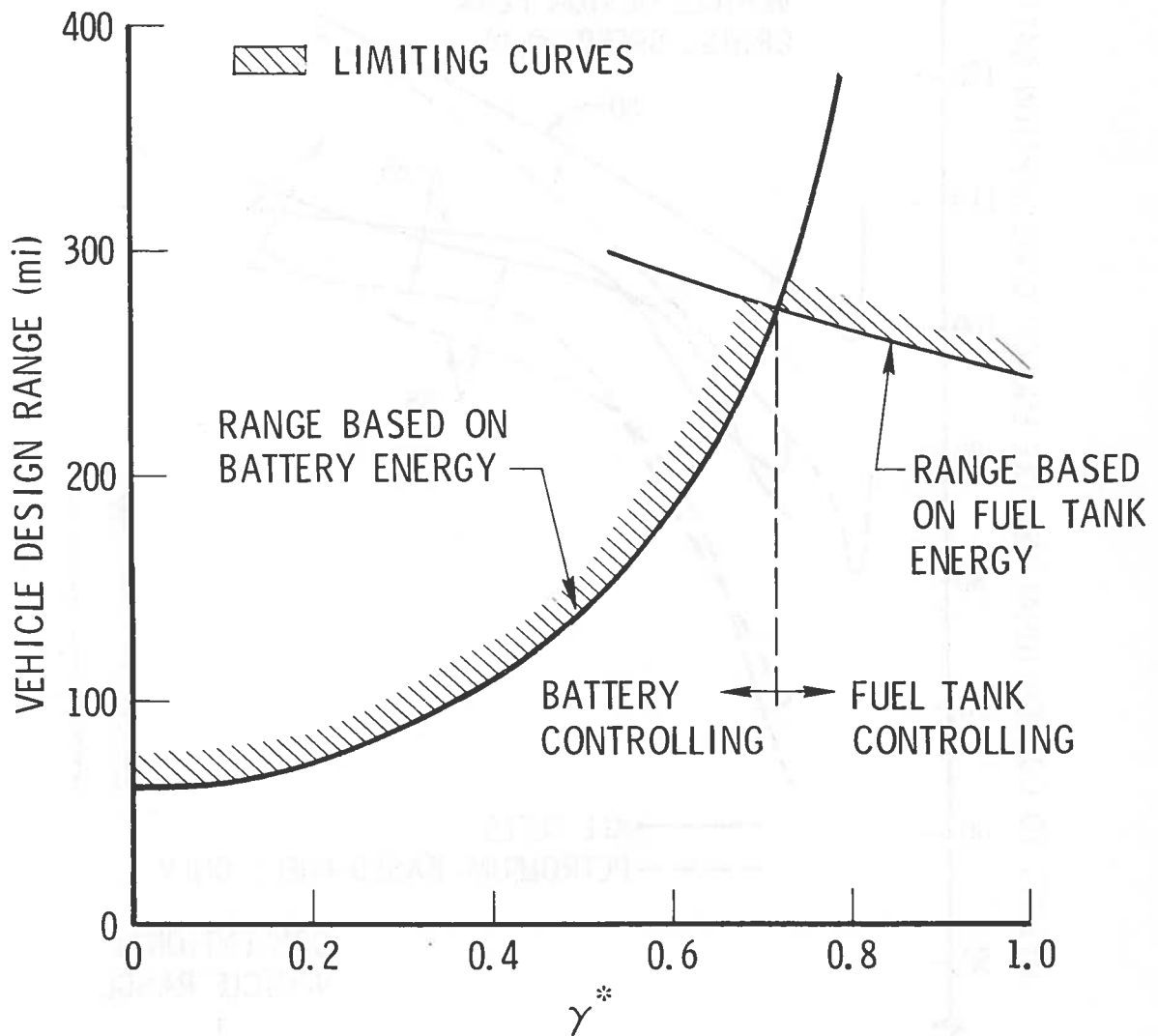
FIGURE 10-31. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



* 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 10-32. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of battery recharge energy supplied by heat engine

FIGURE 10-33. HYBRID HEAT ENGINE/BATTERY VEHICLE OPERATIONAL RANGE: 4000-LB CAR, 65-MPH DESIGN CRUISE SPEED, SERIES CONFIGURATION

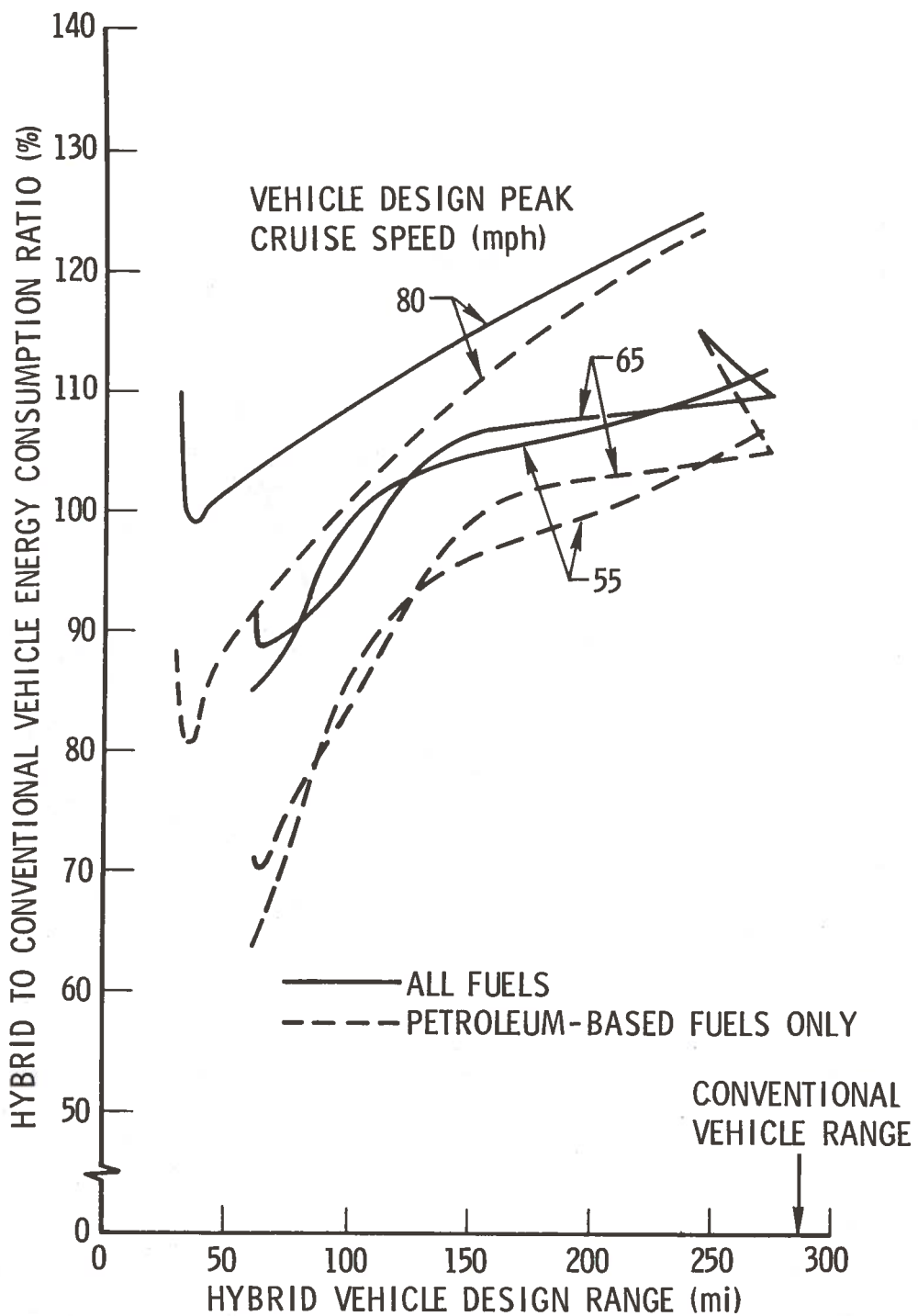


FIGURE 10-34. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE WEIGHT = 4000 LB, SERIES CONFIGURATION

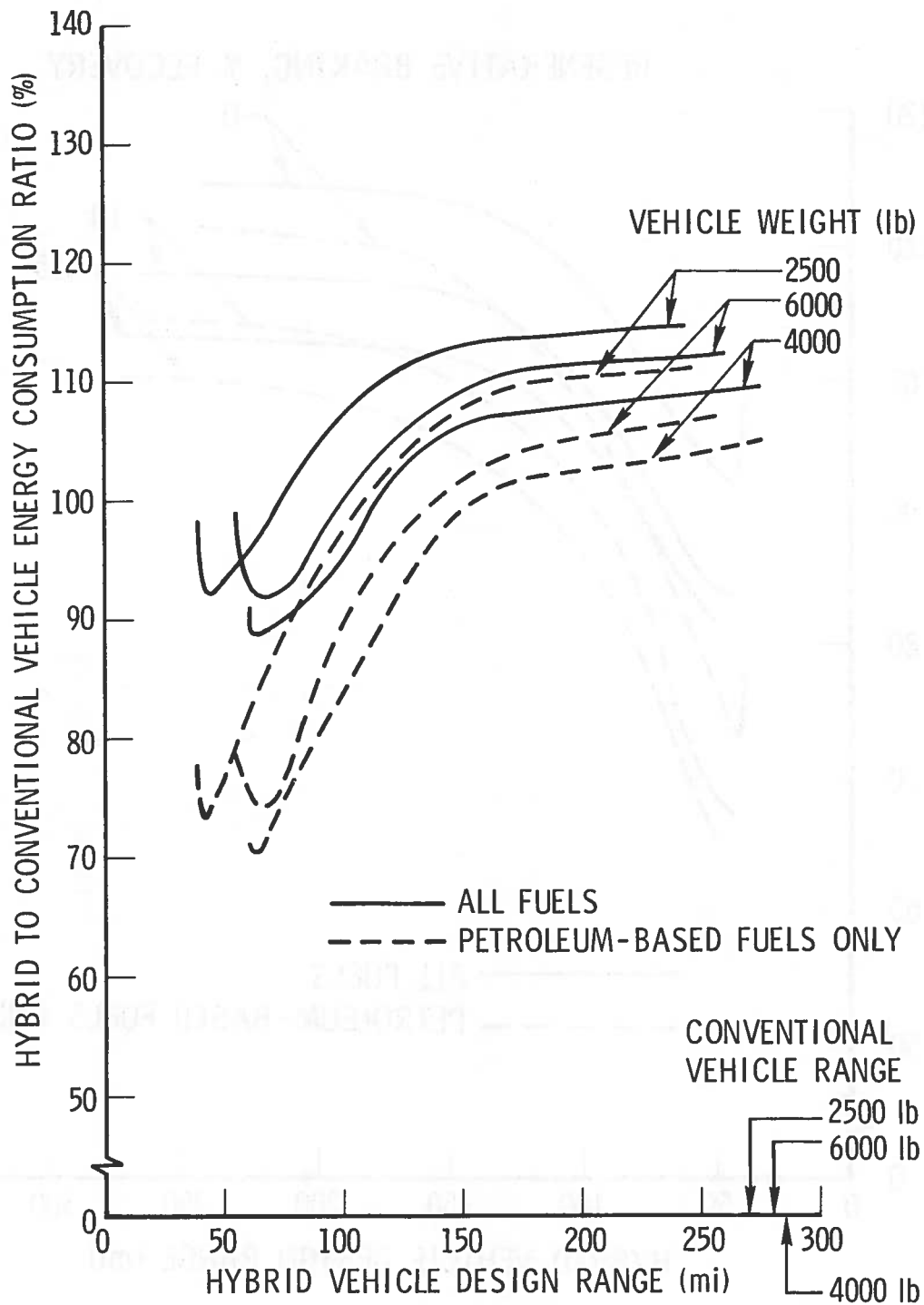


FIGURE 10-35. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION

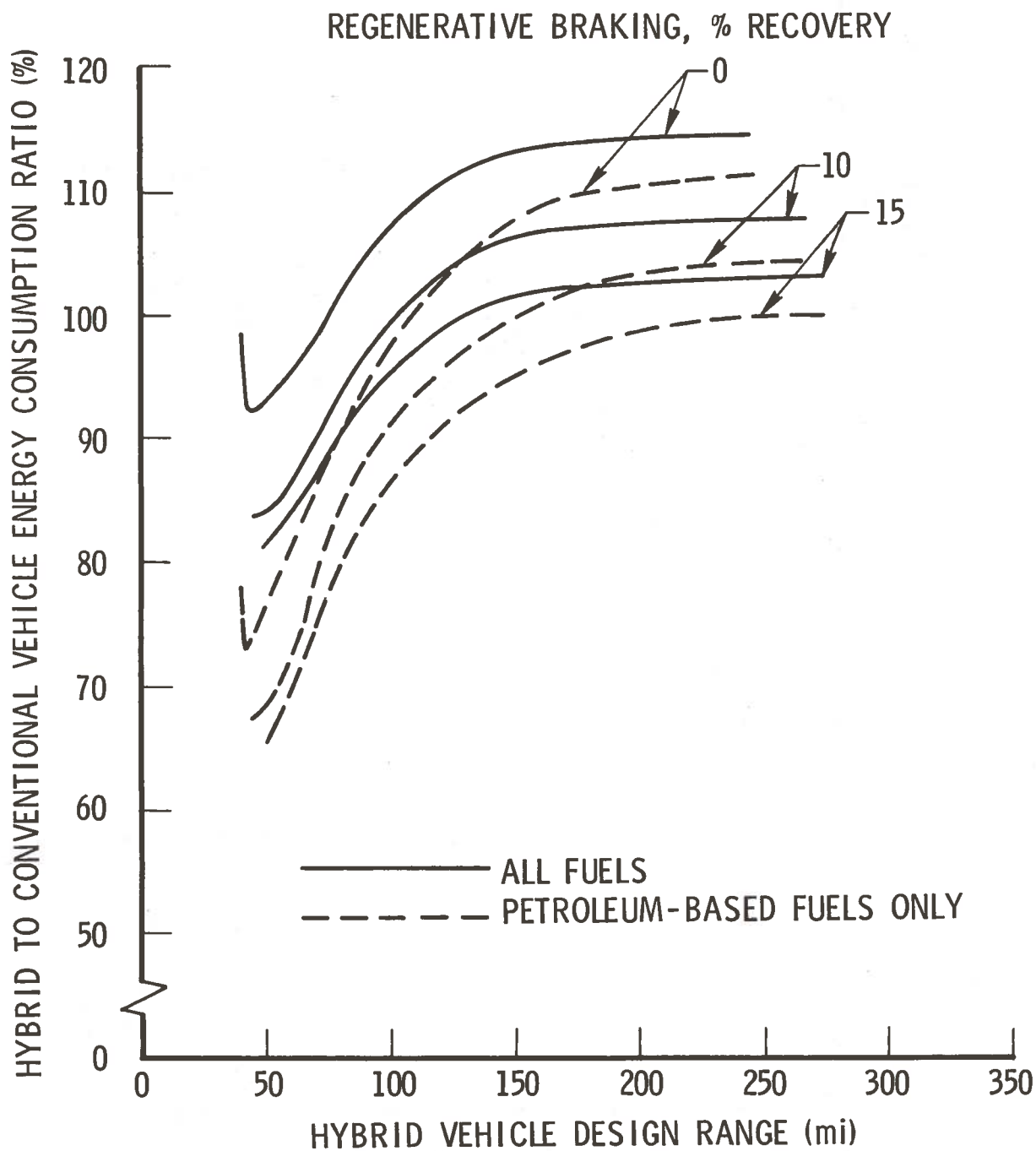


FIGURE 10-36. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, SERIES CONFIGURATION

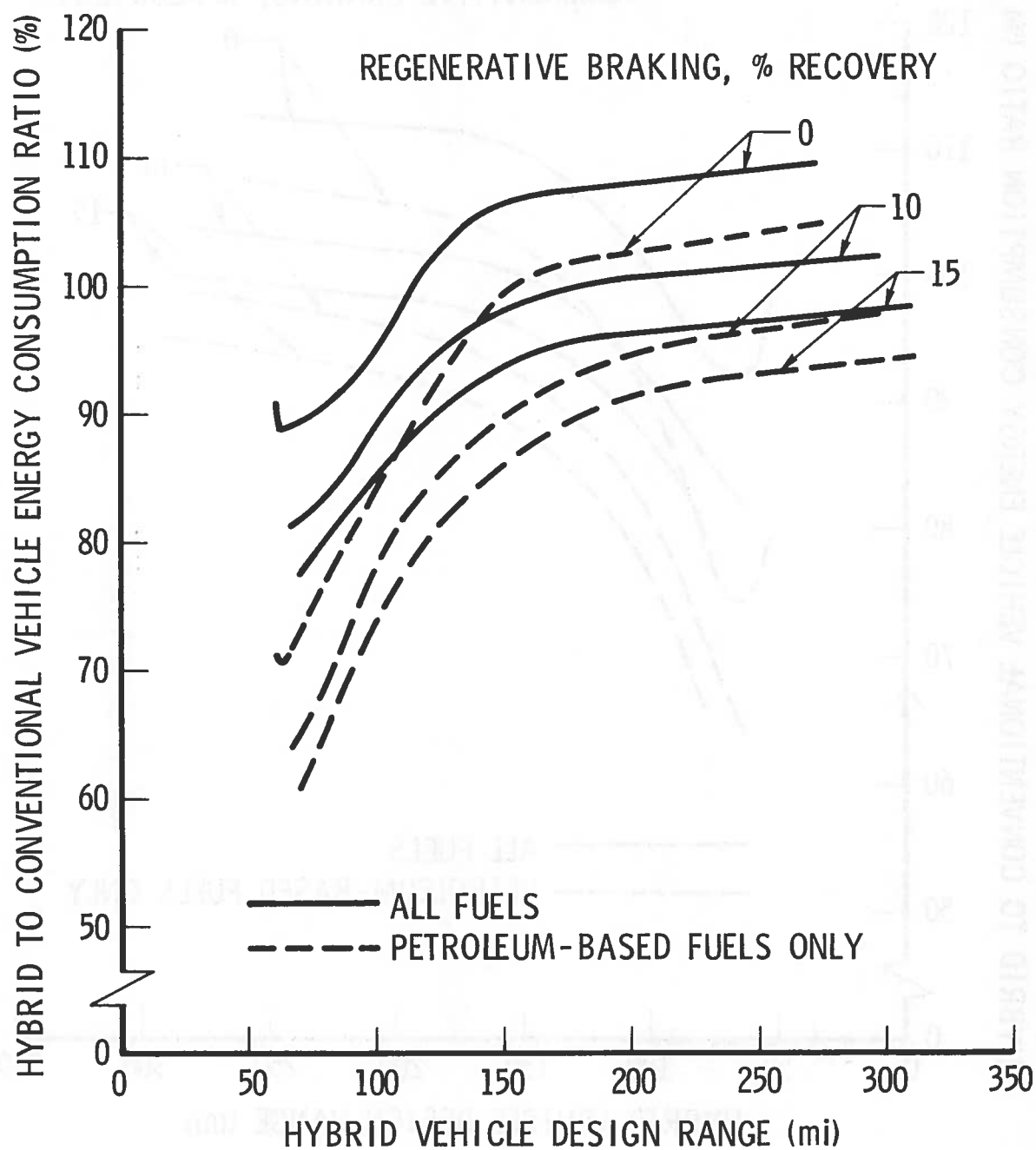


FIGURE 10-37. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, SERIES CONFIGURATION

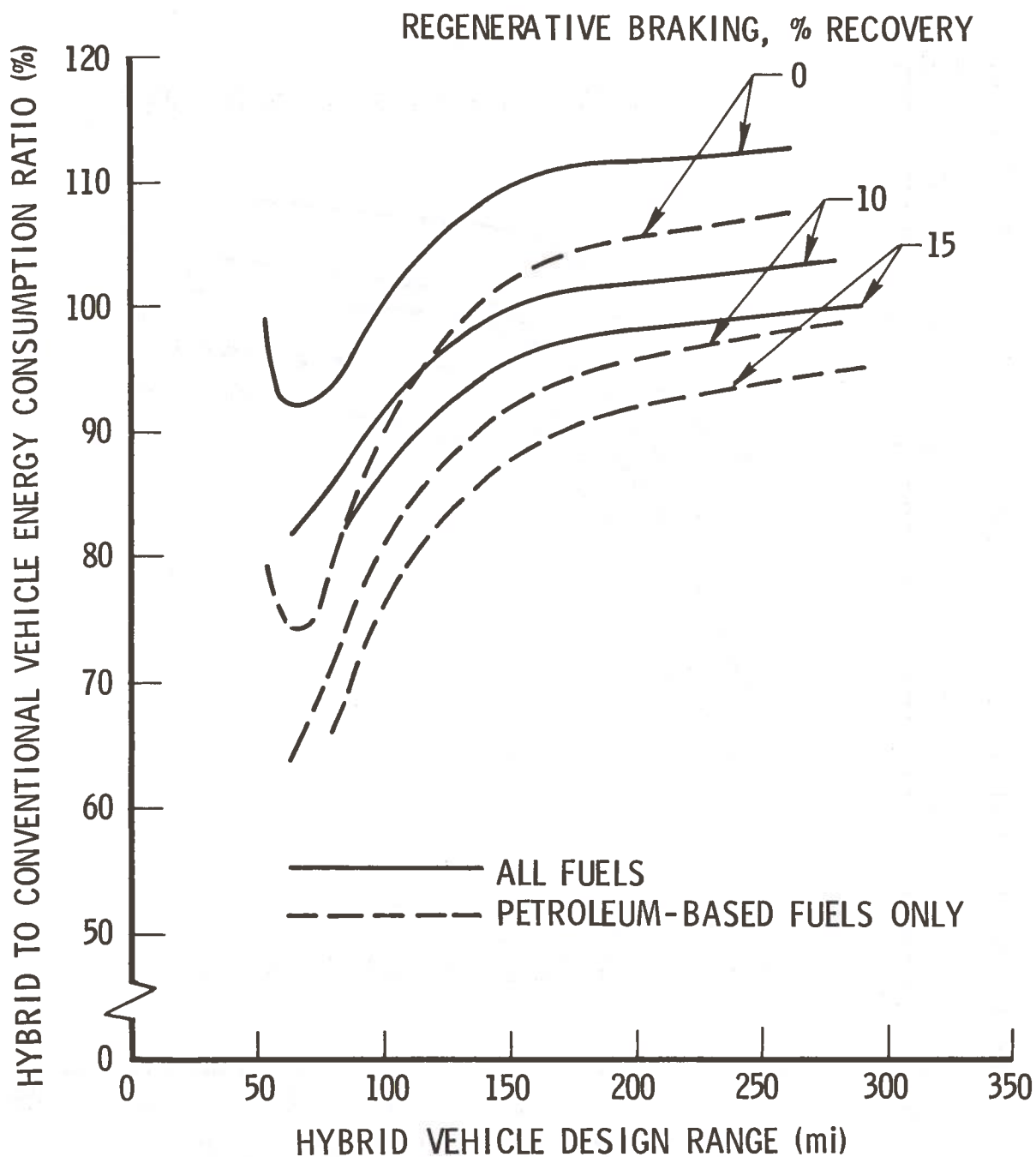


FIGURE 10-38. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, SERIES CONFIGURATION

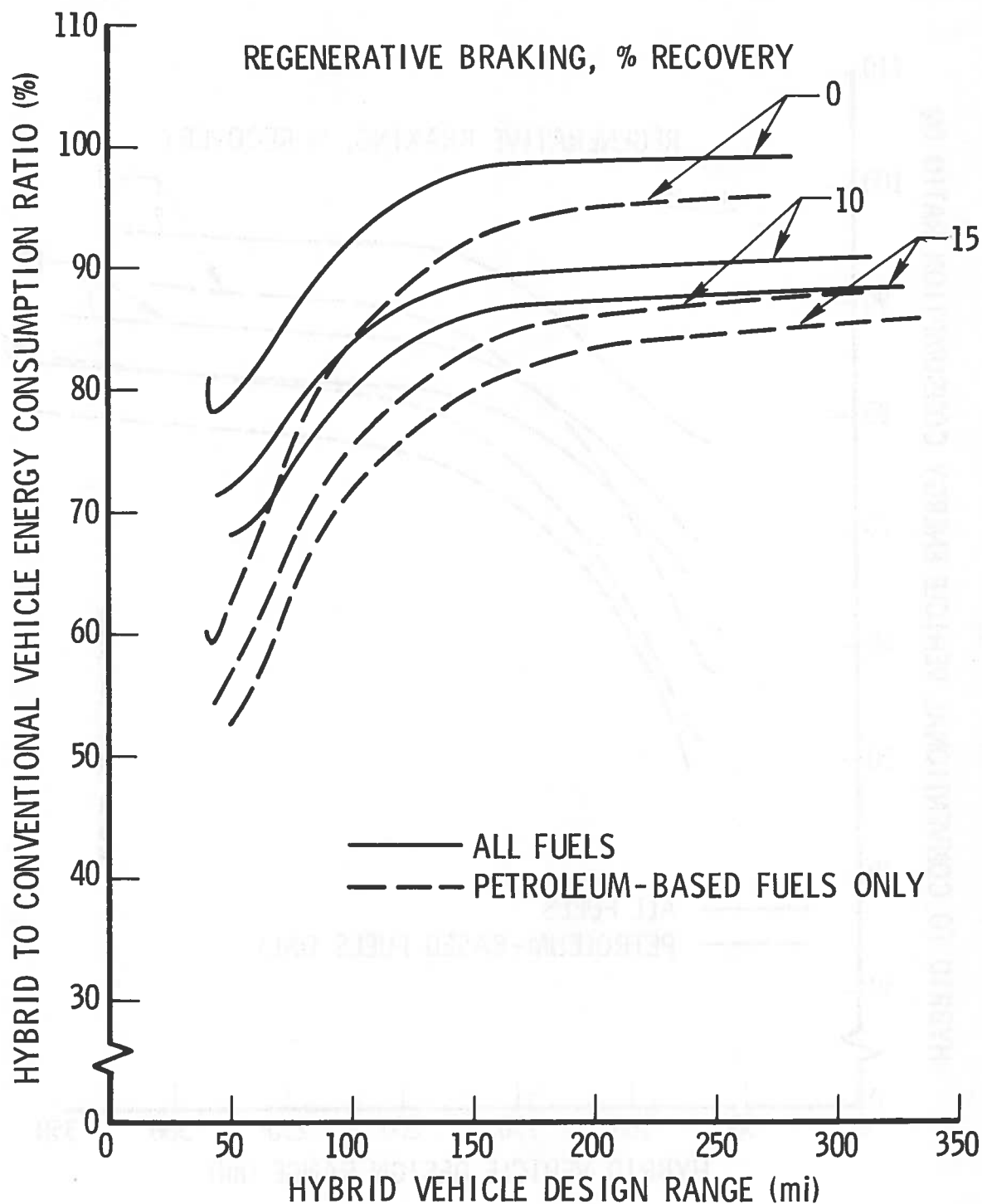


FIGURE 10-39. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, PARALLEL CONFIGURATION

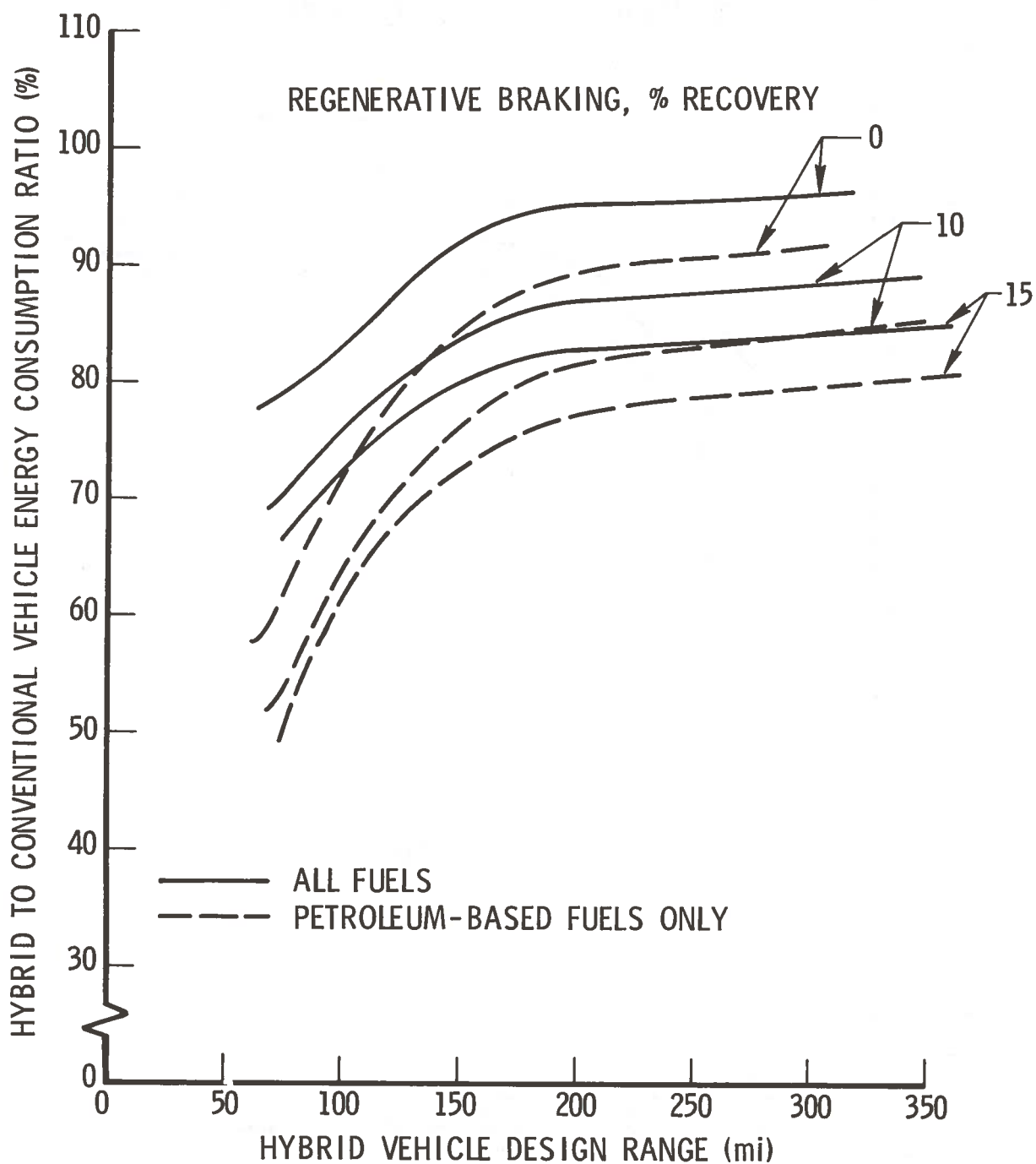


FIGURE 10-40. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, PARALLEL CONFIGURATION

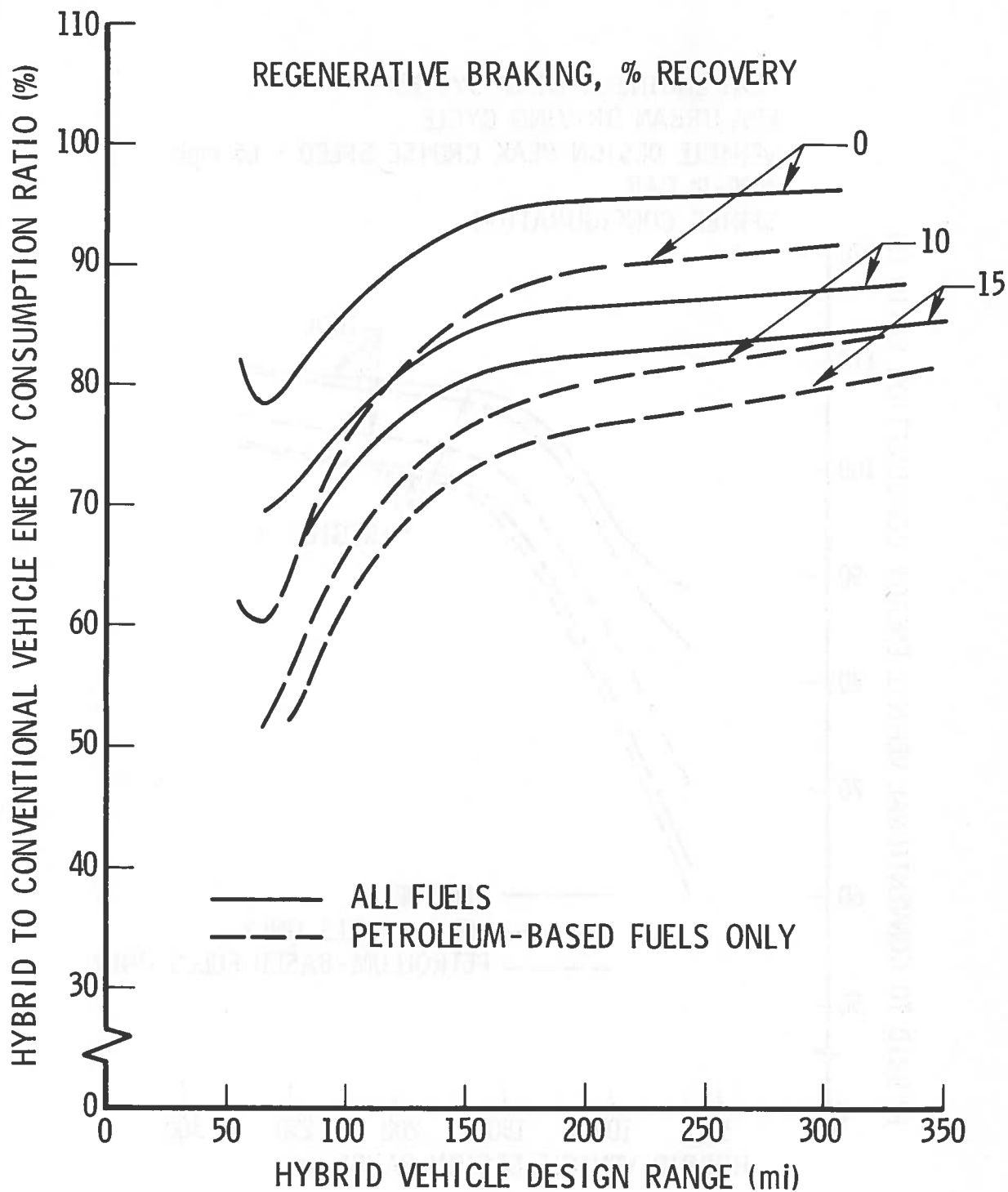


FIGURE 10-41. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, PARALLEL CONFIGURATION

HEAT ENGINE/BATTERY SYSTEM
 EPA URBAN DRIVING CYCLE
 VEHICLE DESIGN PEAK CRUISE SPEED = 65 mph
 4000-lb CAR
 SERIES CONFIGURATION

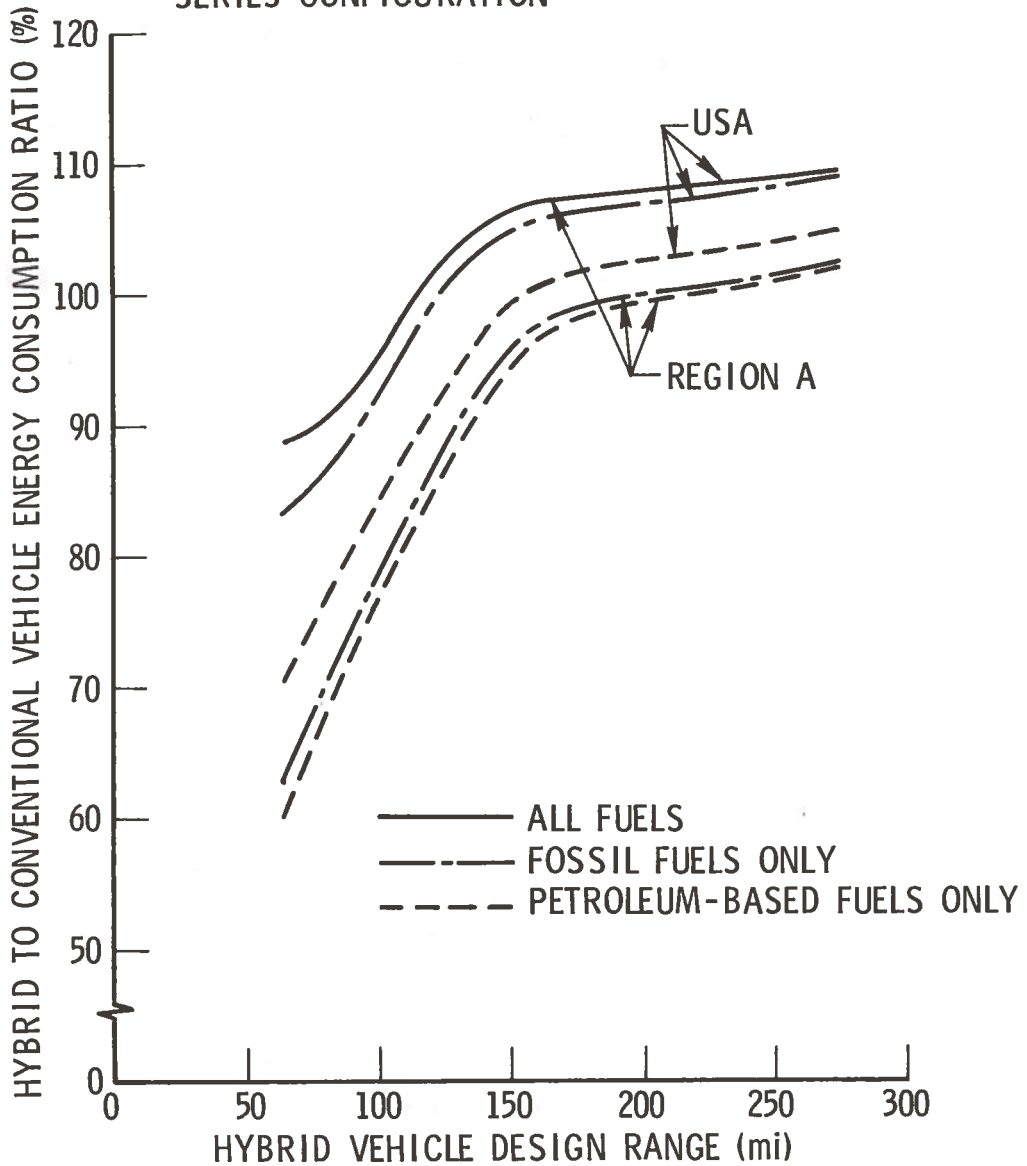


FIGURE 10-42. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION A, NORTHERN PACIFIC STATES

HEAT ENGINE/BATTERY SYSTEM
 EPA URBAN DRIVING CYCLE
 VEHICLE DESIGN PEAK CRUISE SPEED = 65 mph
 4000-lb CAR
 SERIES CONFIGURATION

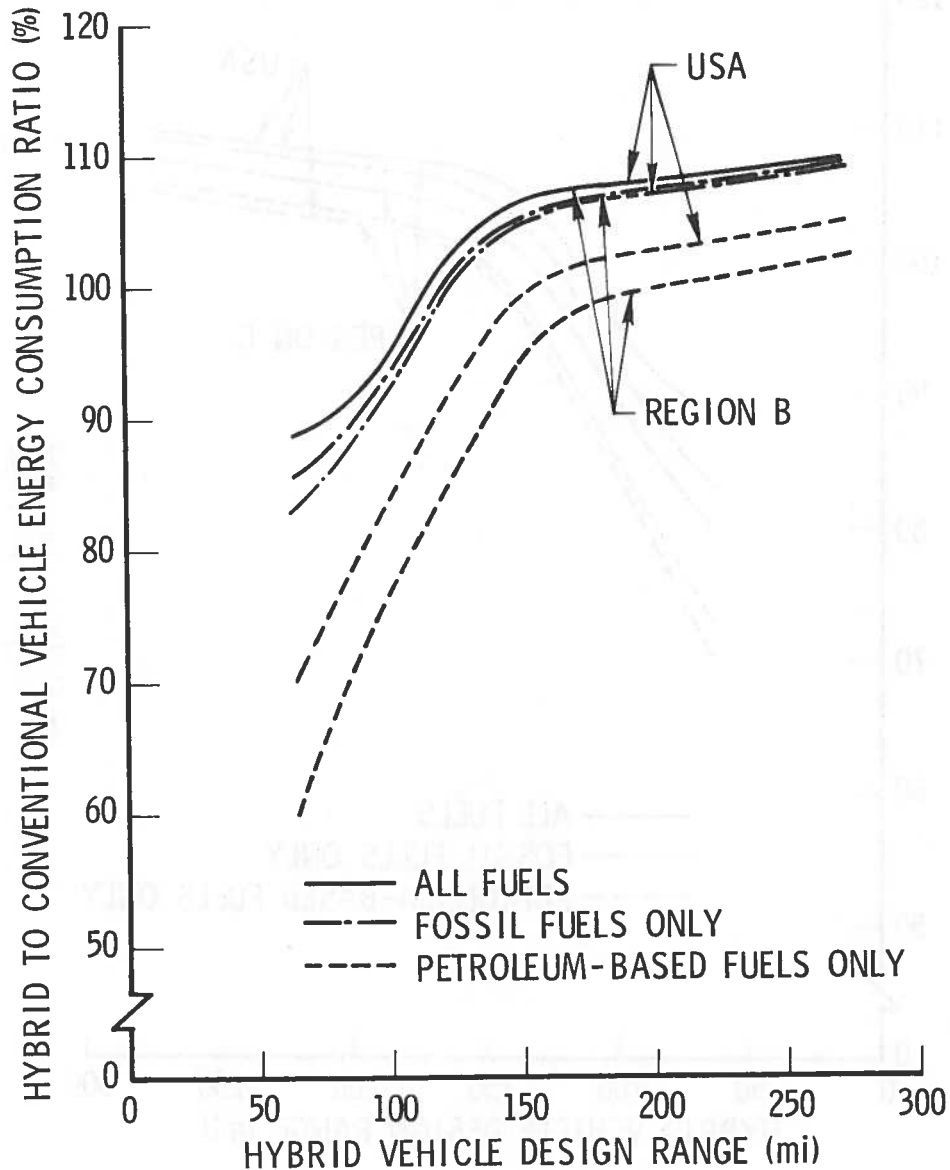


FIGURE 10-43. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION B, EAST-NORTH-CENTRAL STATES

HEAT ENGINE/BATTERY SYSTEM
 EPA URBAN DRIVING CYCLE
 VEHICLE DESIGN PEAK CRUISE SPEED = 65 mph
 4000-lb CAR
 SERIES CONFIGURATION

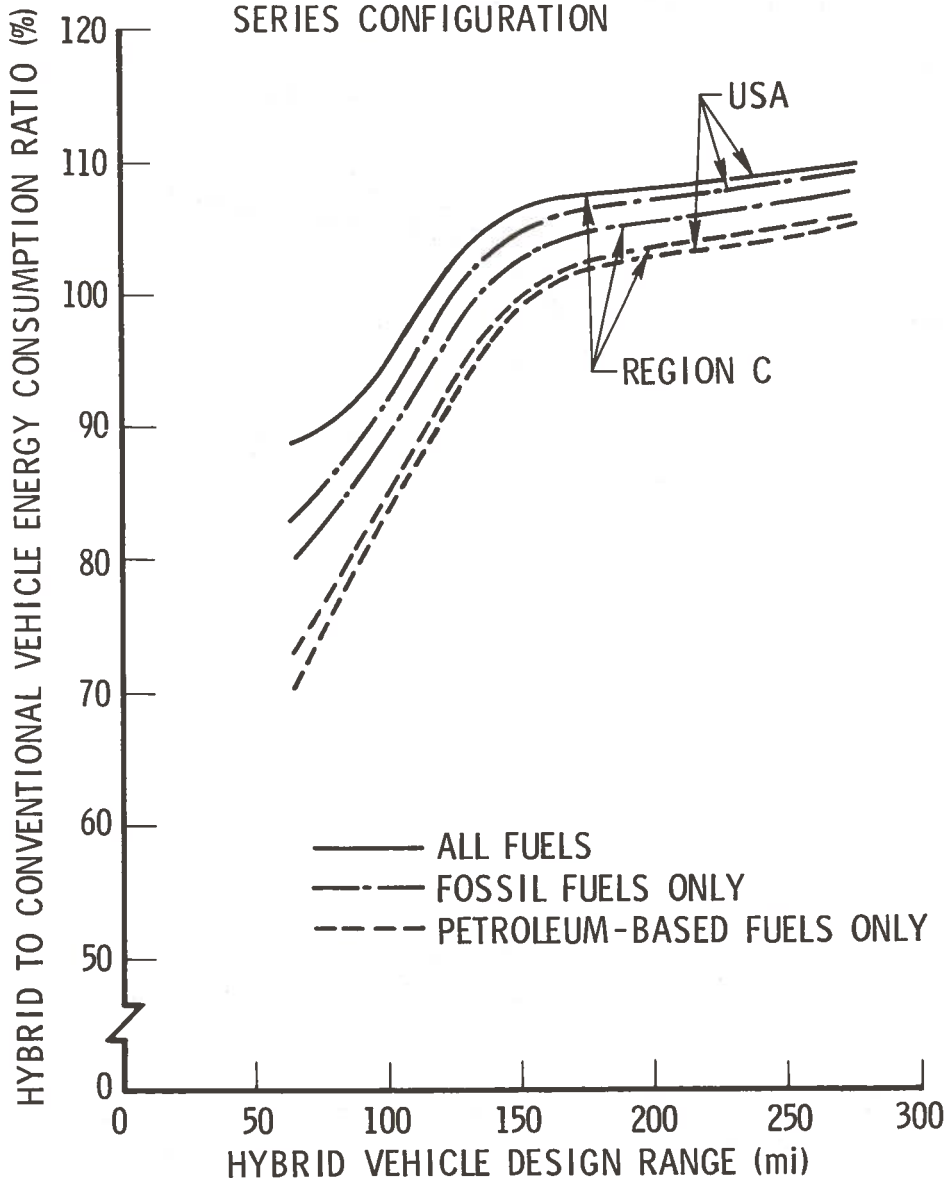


FIGURE 10-44. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION C, NEW ENGLAND AND MIDDLE ATLANTIC STATES

HEAT ENGINE/BATTERY SYSTEM
 EPA URBAN DRIVING CYCLE
 VEHICLE DESIGN PEAK CRUISE SPEED = 65 mph
 4000-lb CAR
 SERIES CONFIGURATION

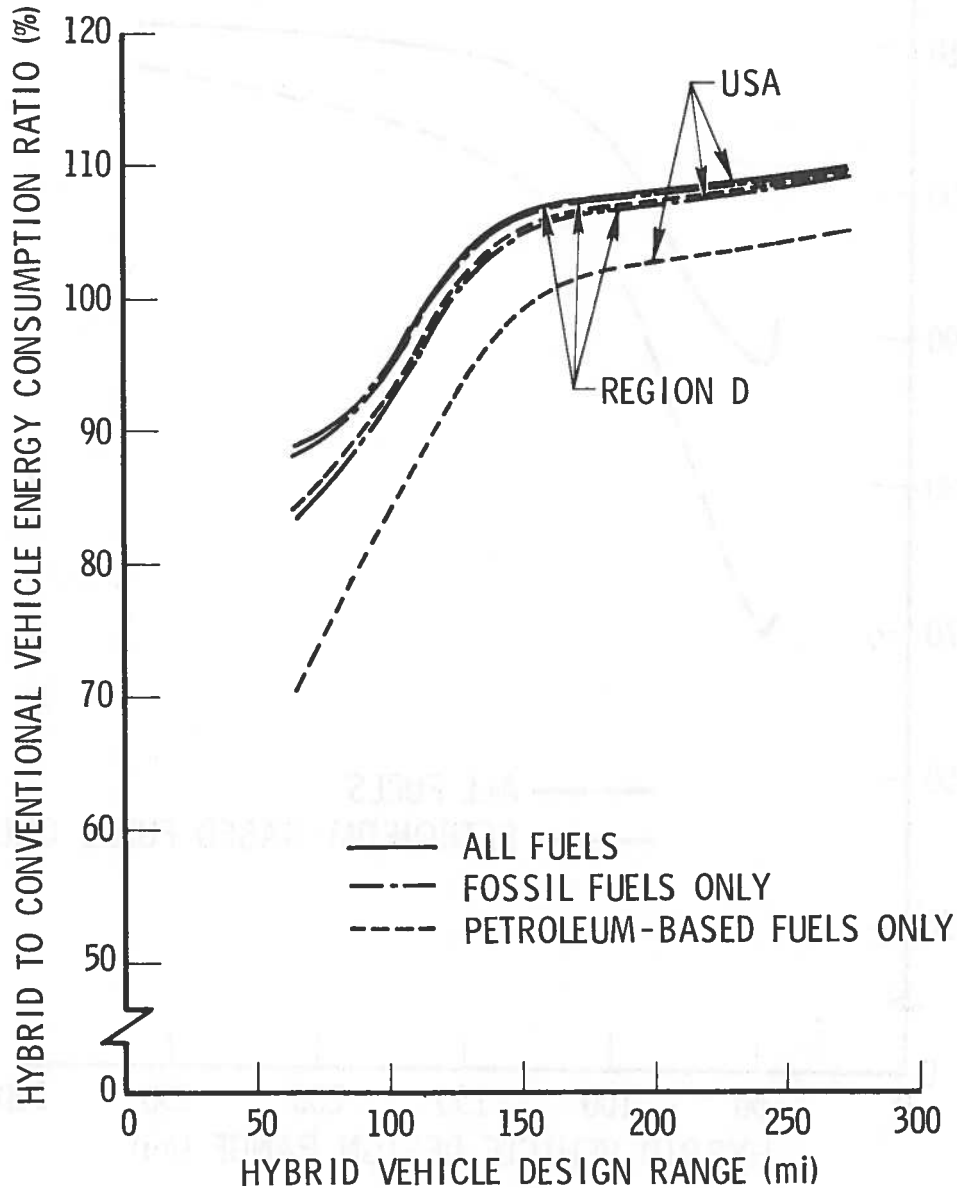


FIGURE 10-45. EFFECT OF GEOGRAPHIC REGION ON HYBRID VEHICLE ENERGY CONSUMPTION: REGION D, WEST-SOUTH-CENTRAL STATES

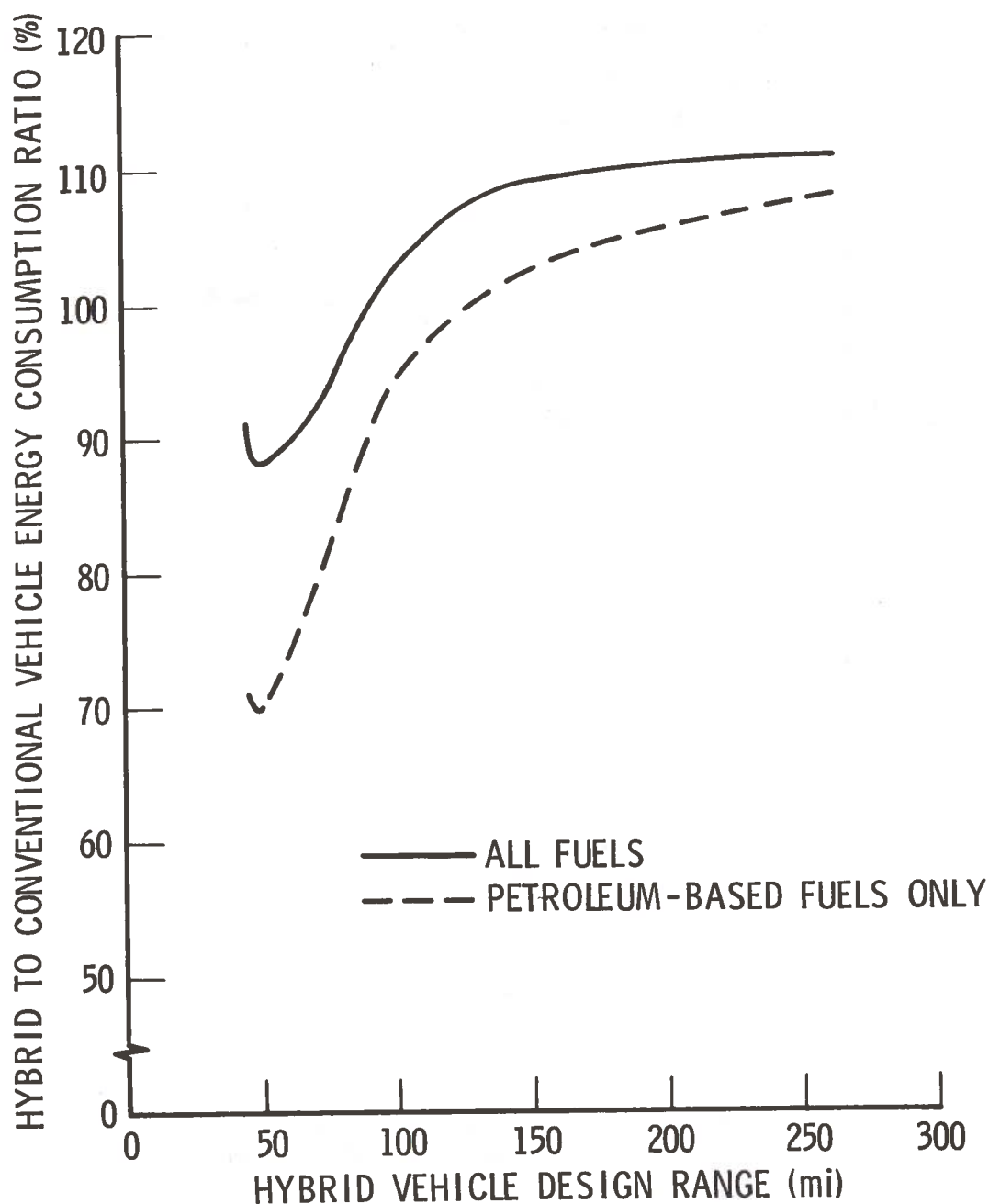


FIGURE 10-46. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, LEAD-ACID BATTERY SYSTEM, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, SERIES CONFIGURATION

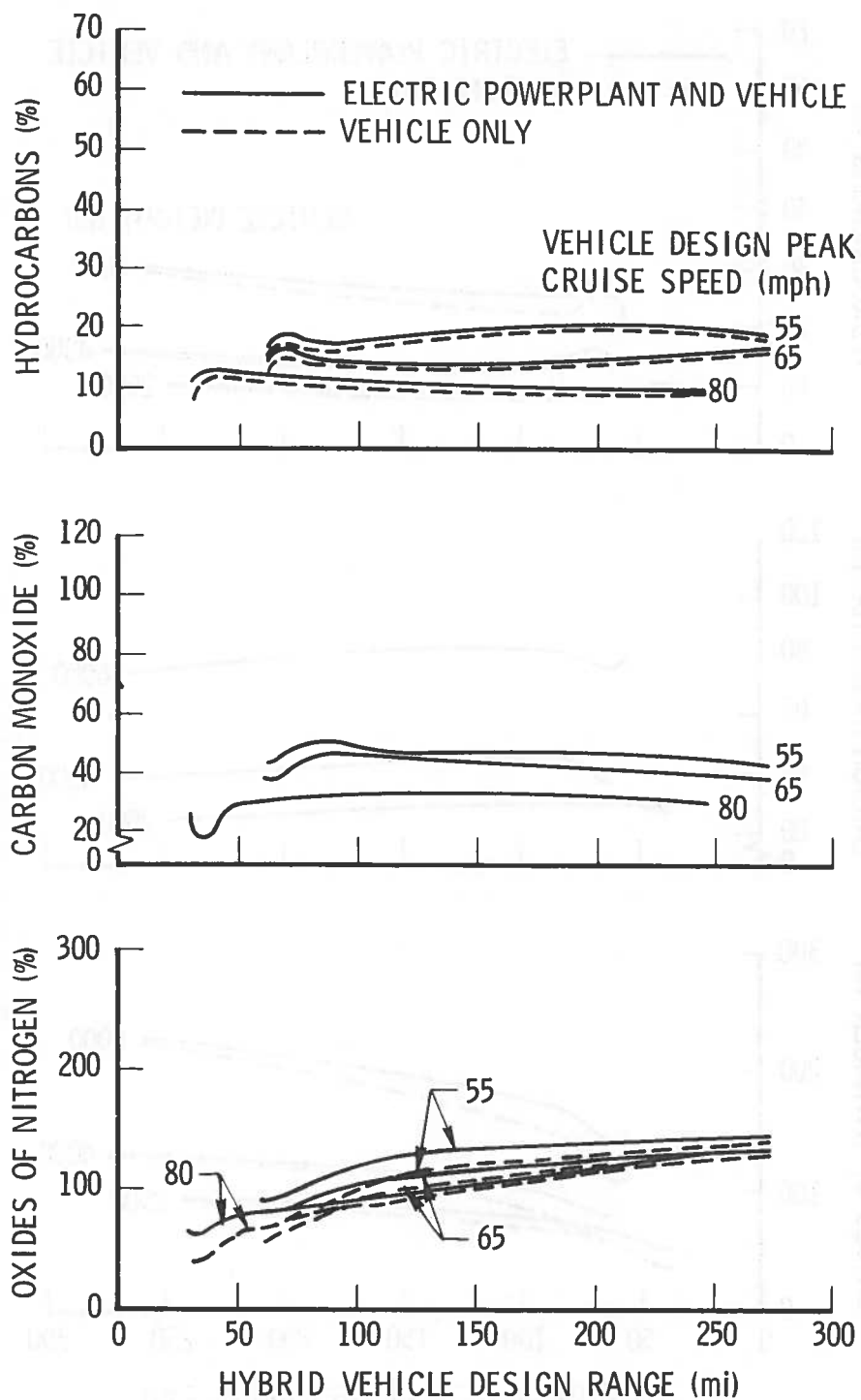


FIGURE 10-47. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE WEIGHT = 4000 LB, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

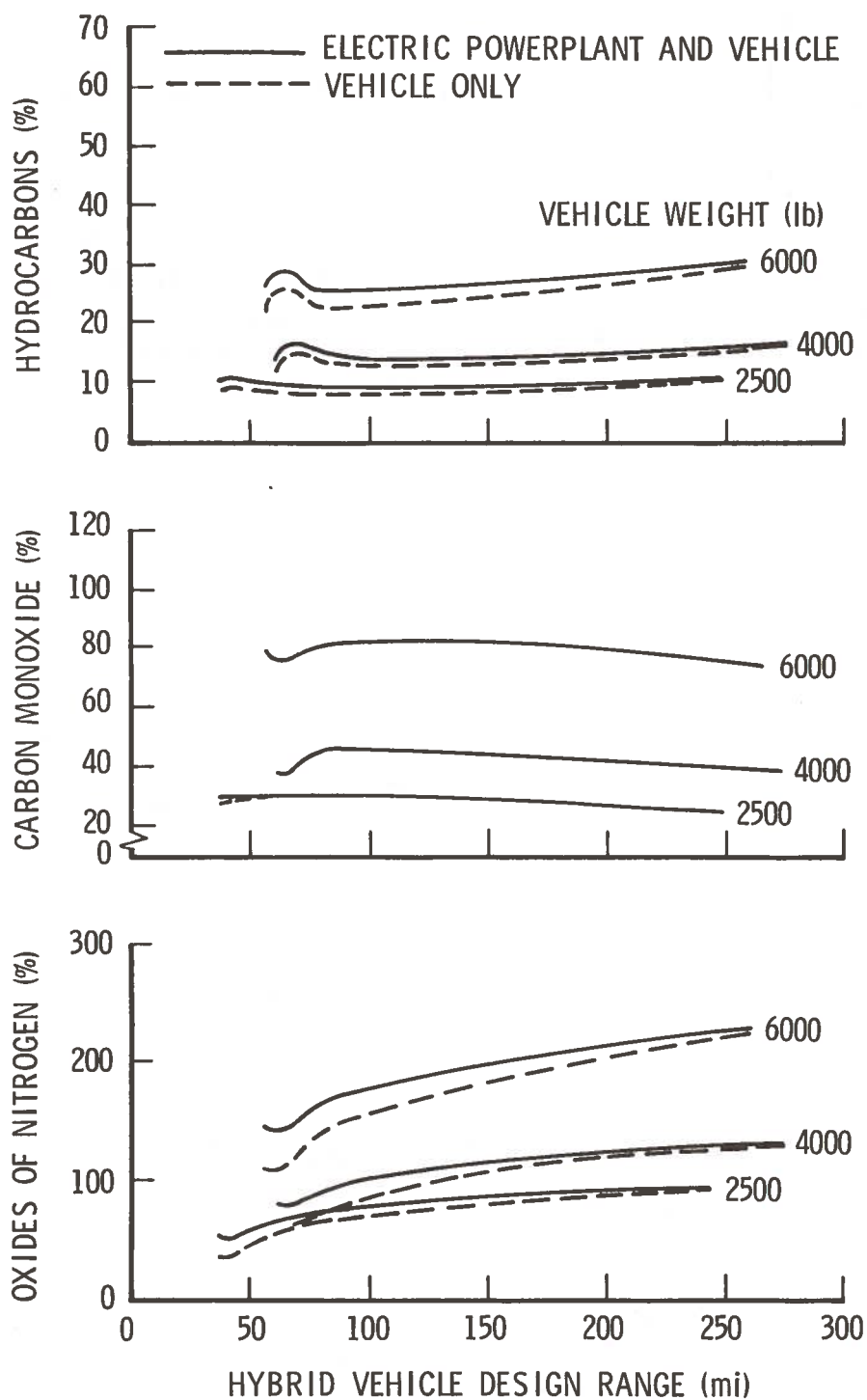


FIGURE 10-48. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

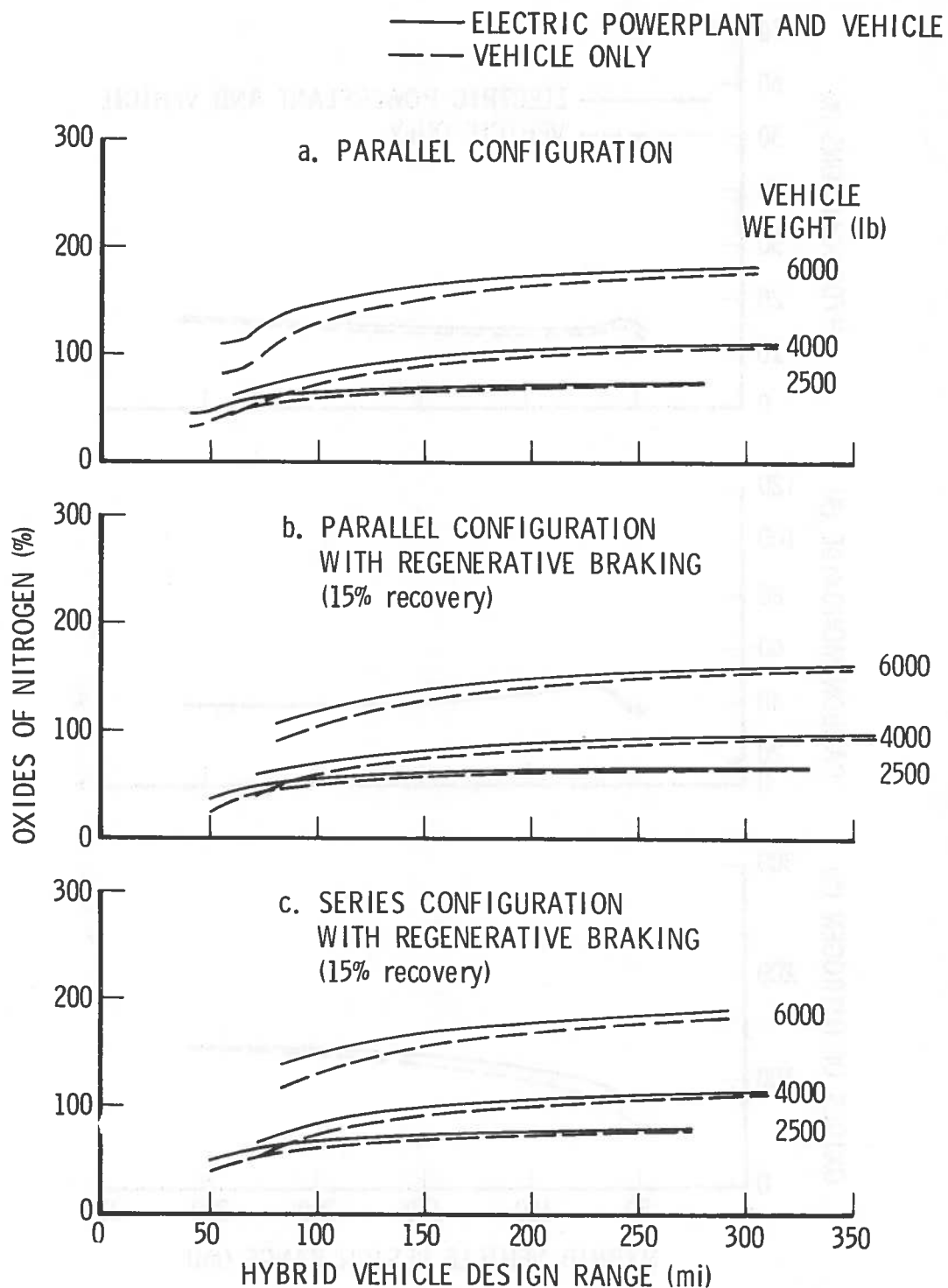


FIGURE 10-49. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED NO_x EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH (REF.: 1975-76 FEDERAL STANDARDS)

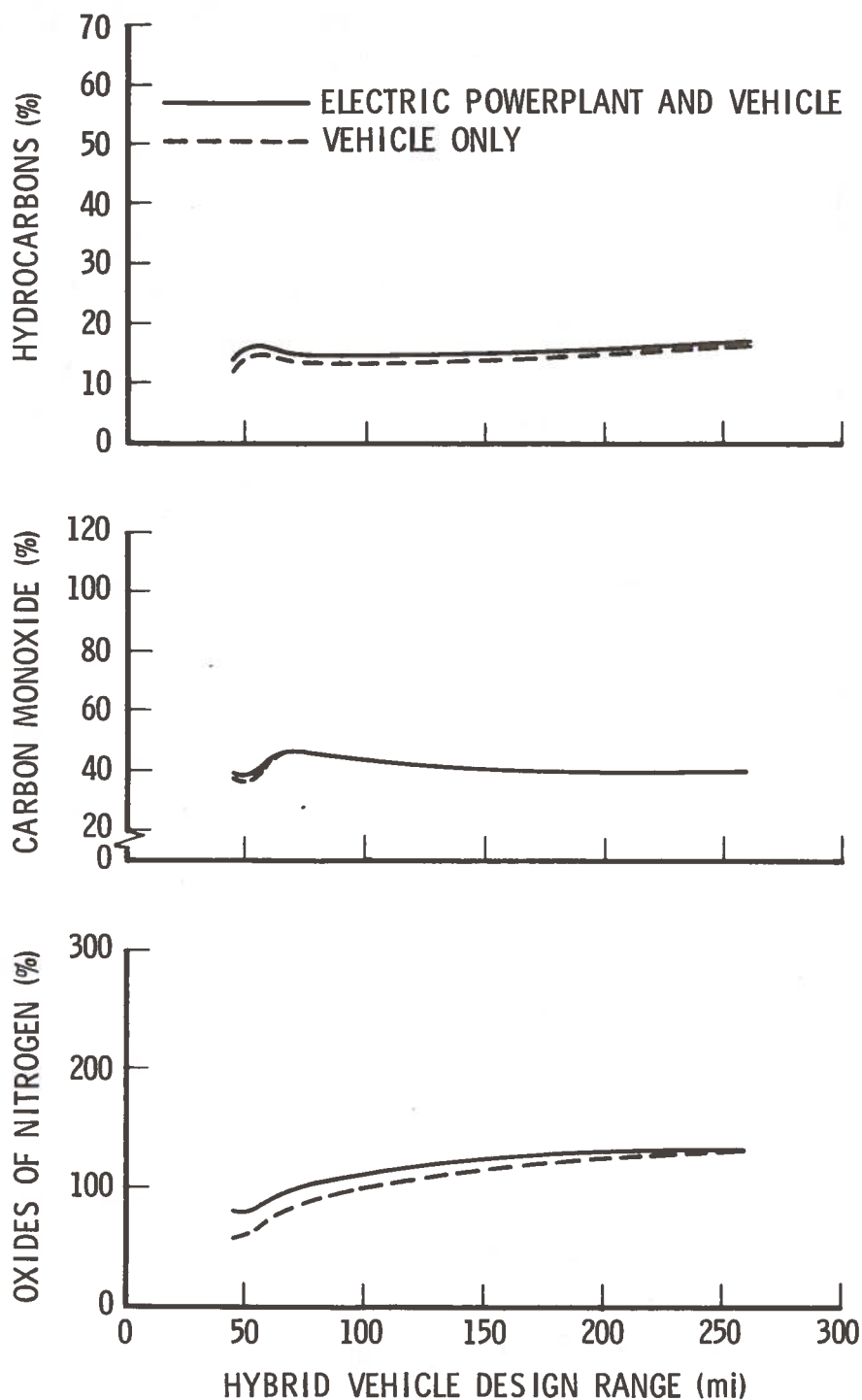


FIGURE 10-50. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, LEAD-ACID BATTERY SYSTEM, VEHICLE WEIGHT= 4000 LB, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

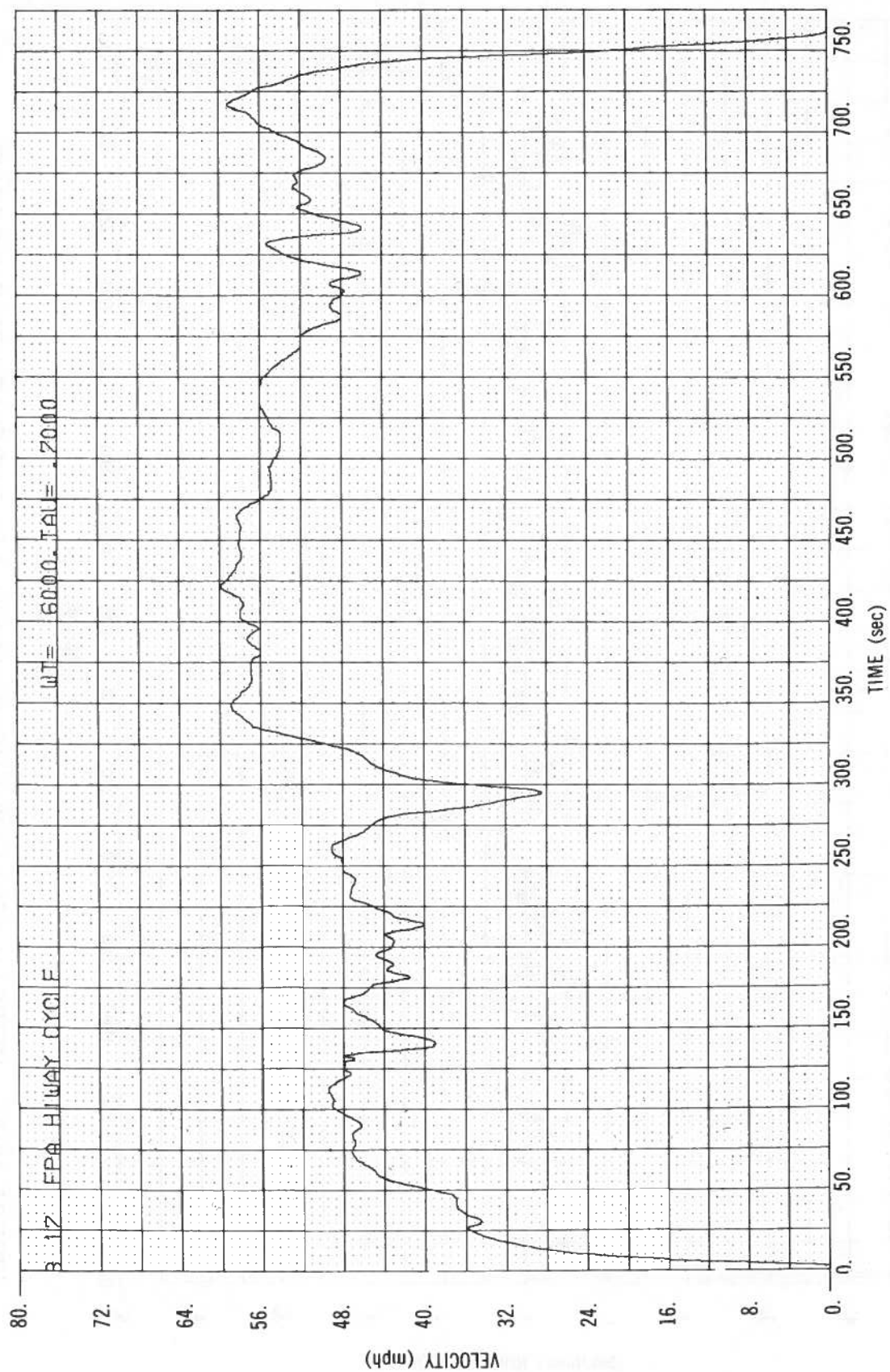


FIGURE 10-51. VEHICLE VELOCITY HISTORY: EPA HIGHWAY DRIVING CYCLE

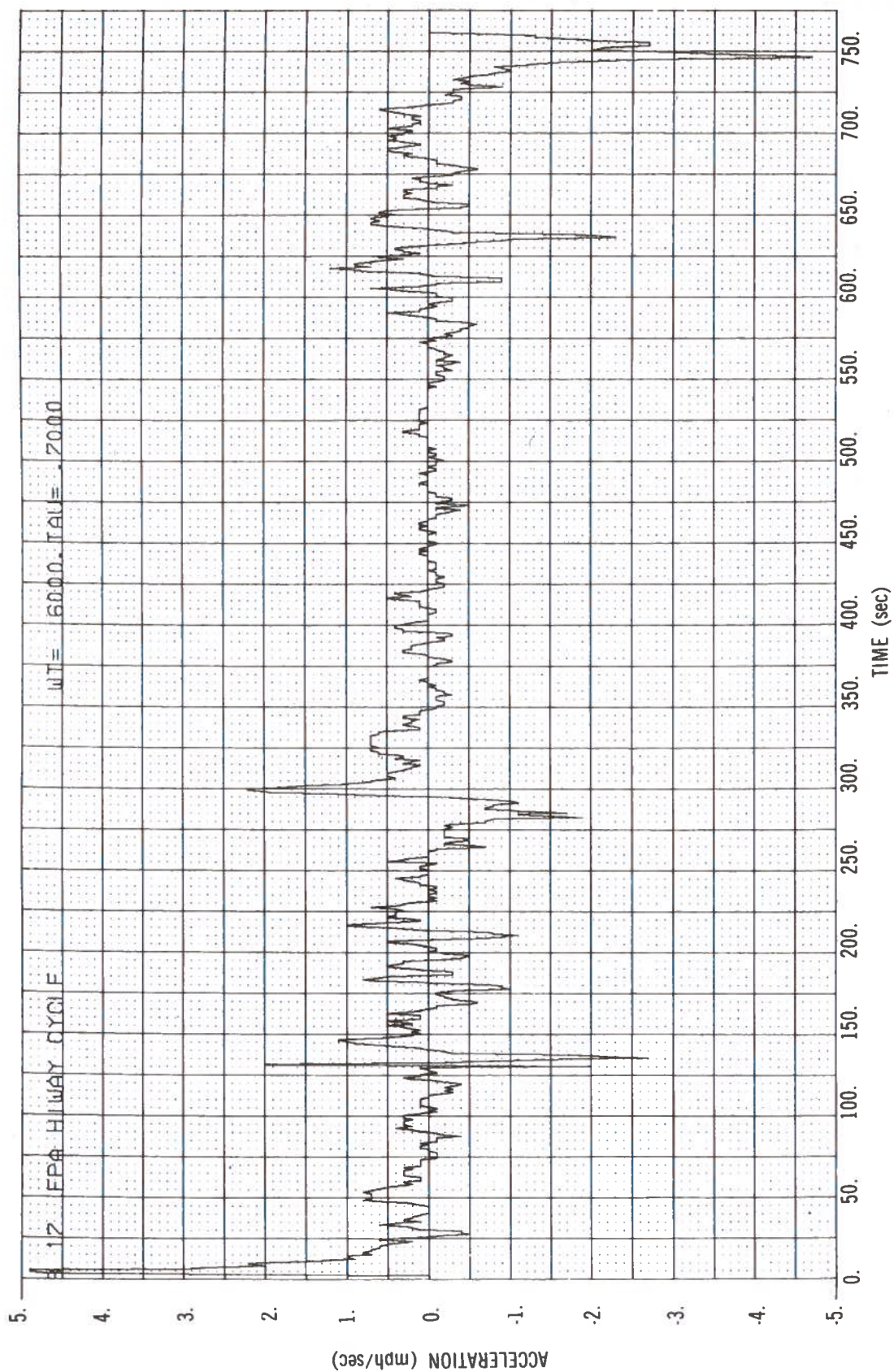


FIGURE 10-52. VEHICLE ACCELERATION HISTORY: EPA HIGHWAY DRIVING CYCLE

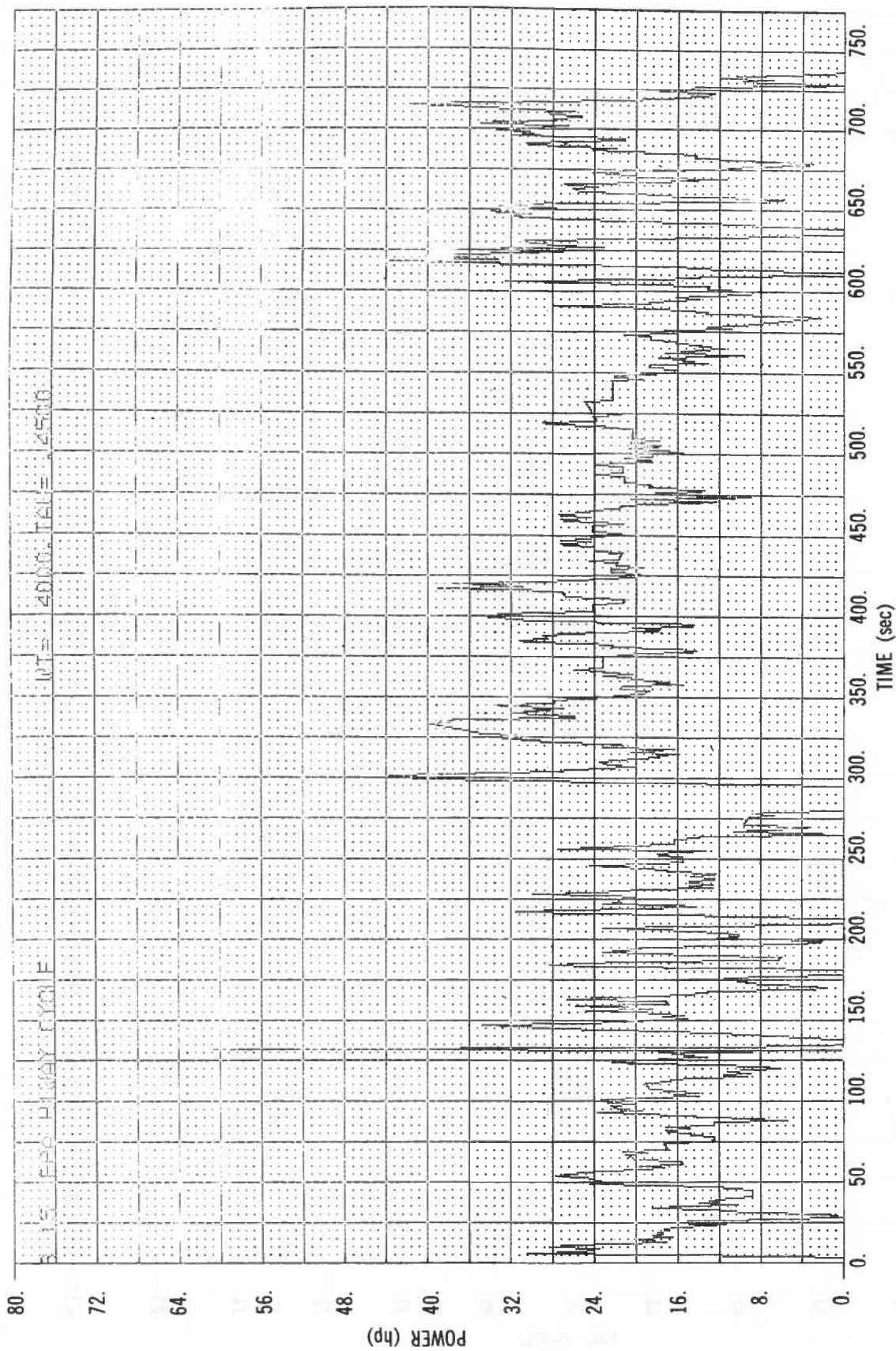


FIGURE 10-53. HISTORY OF TOTAL WHEEL POWER REQUIRED BY 4000-LB CAR
ON EPA HIGHWAY DRIVING CYCLE

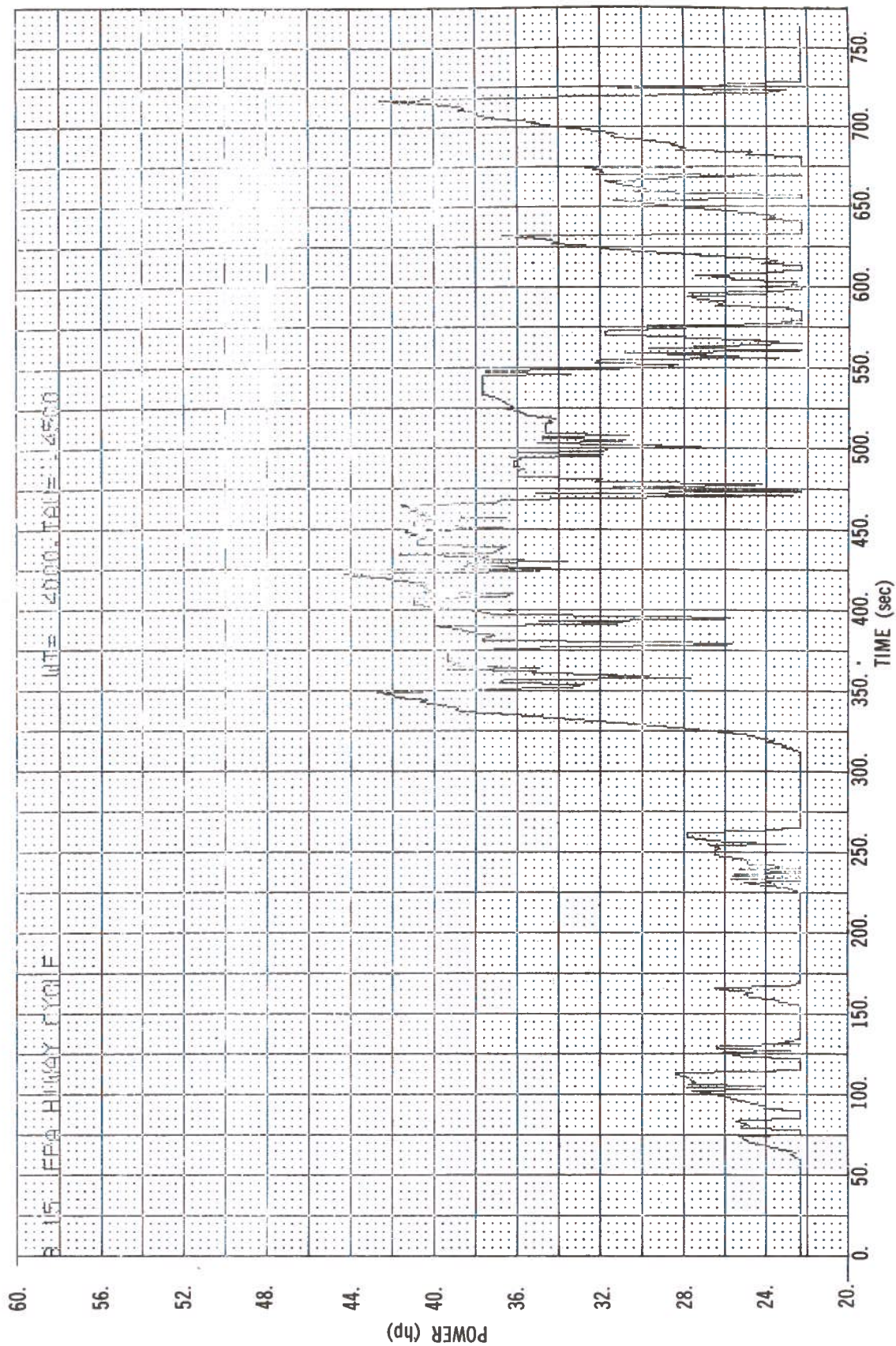


FIGURE 10-54. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA HIGHWAY DRIVING CYCLE, $\tau = 0.45$

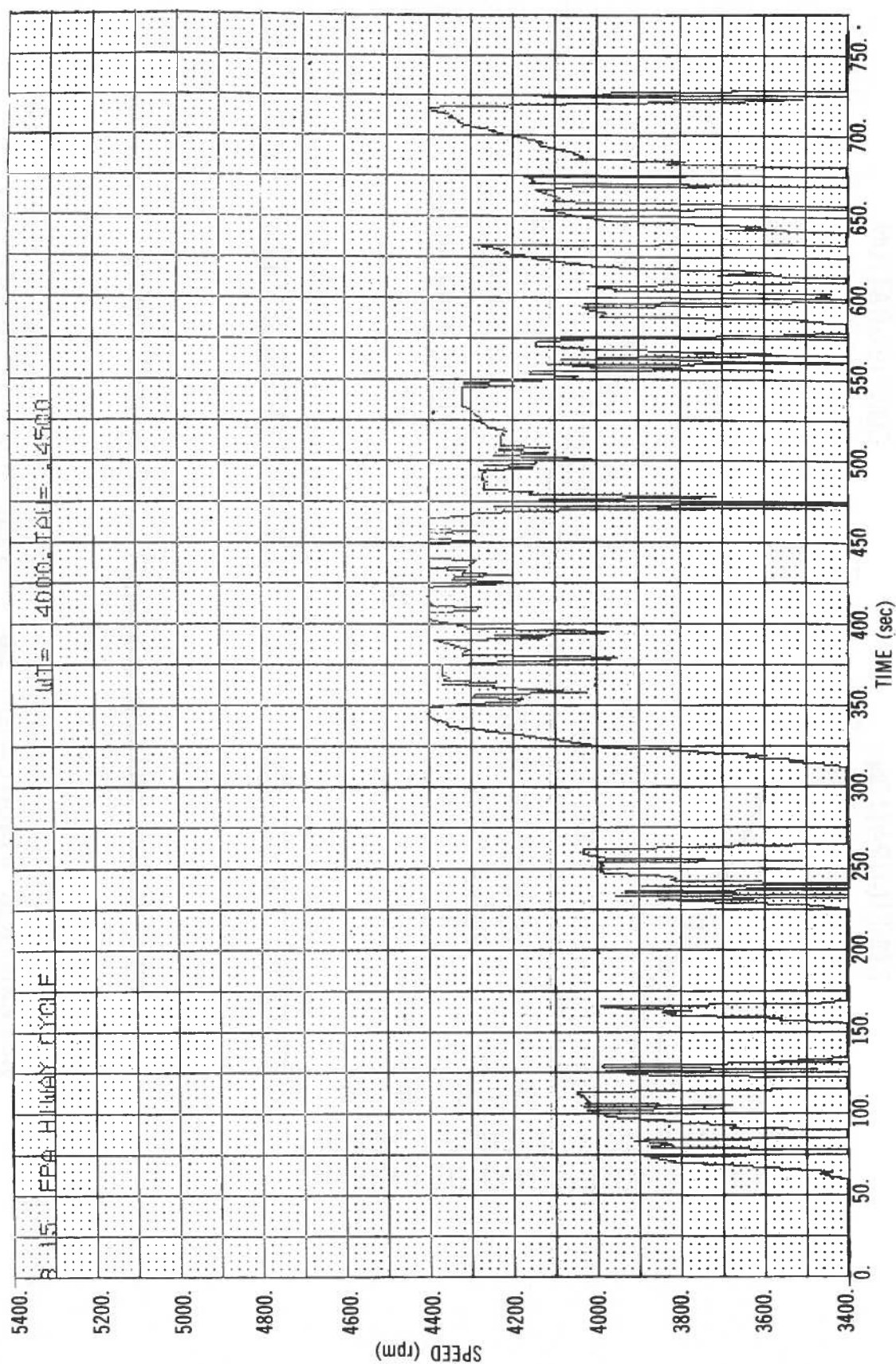
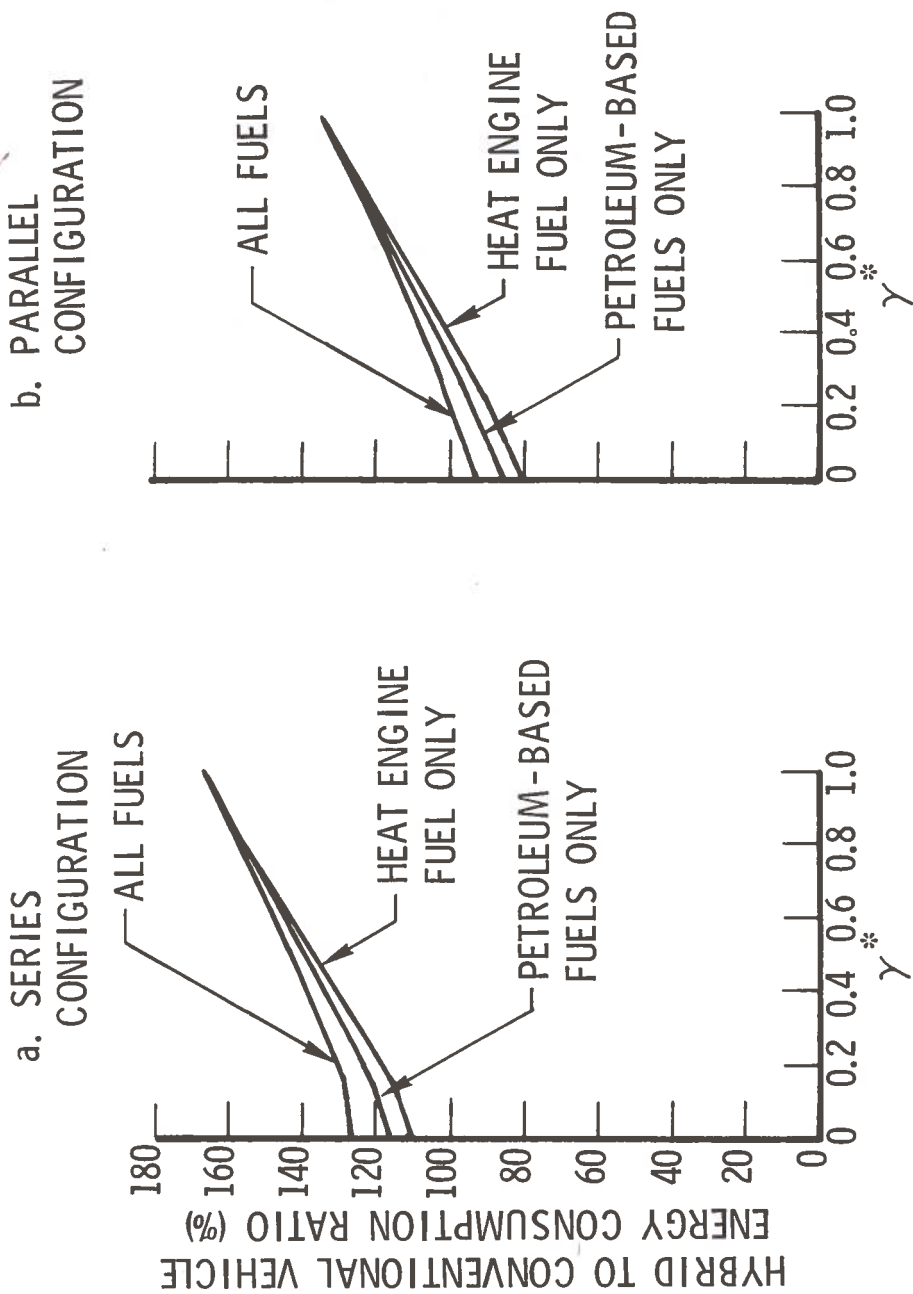
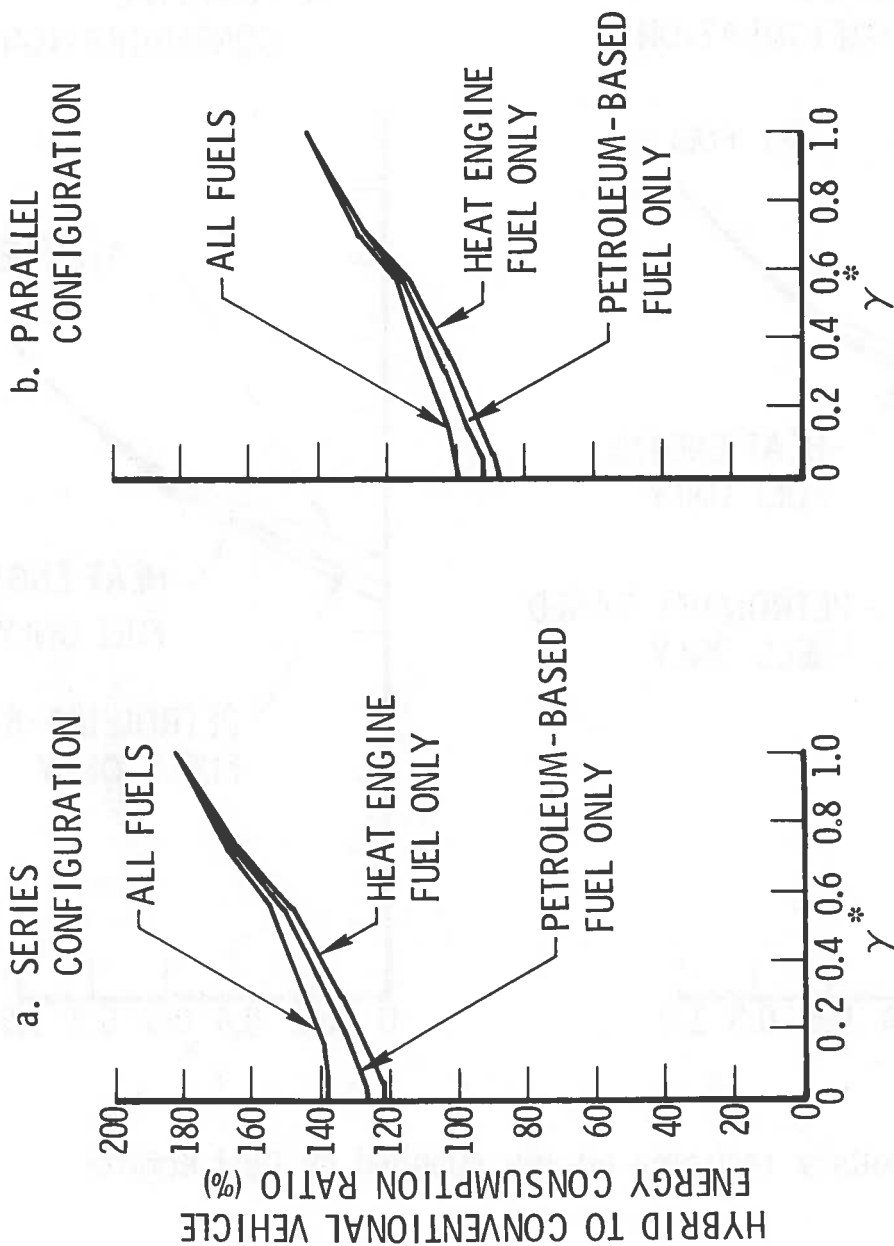


FIGURE 10-55. ENGINE SPEED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, EPA HIGHWAY DRIVING CYCLE, $\tau = 0.45$



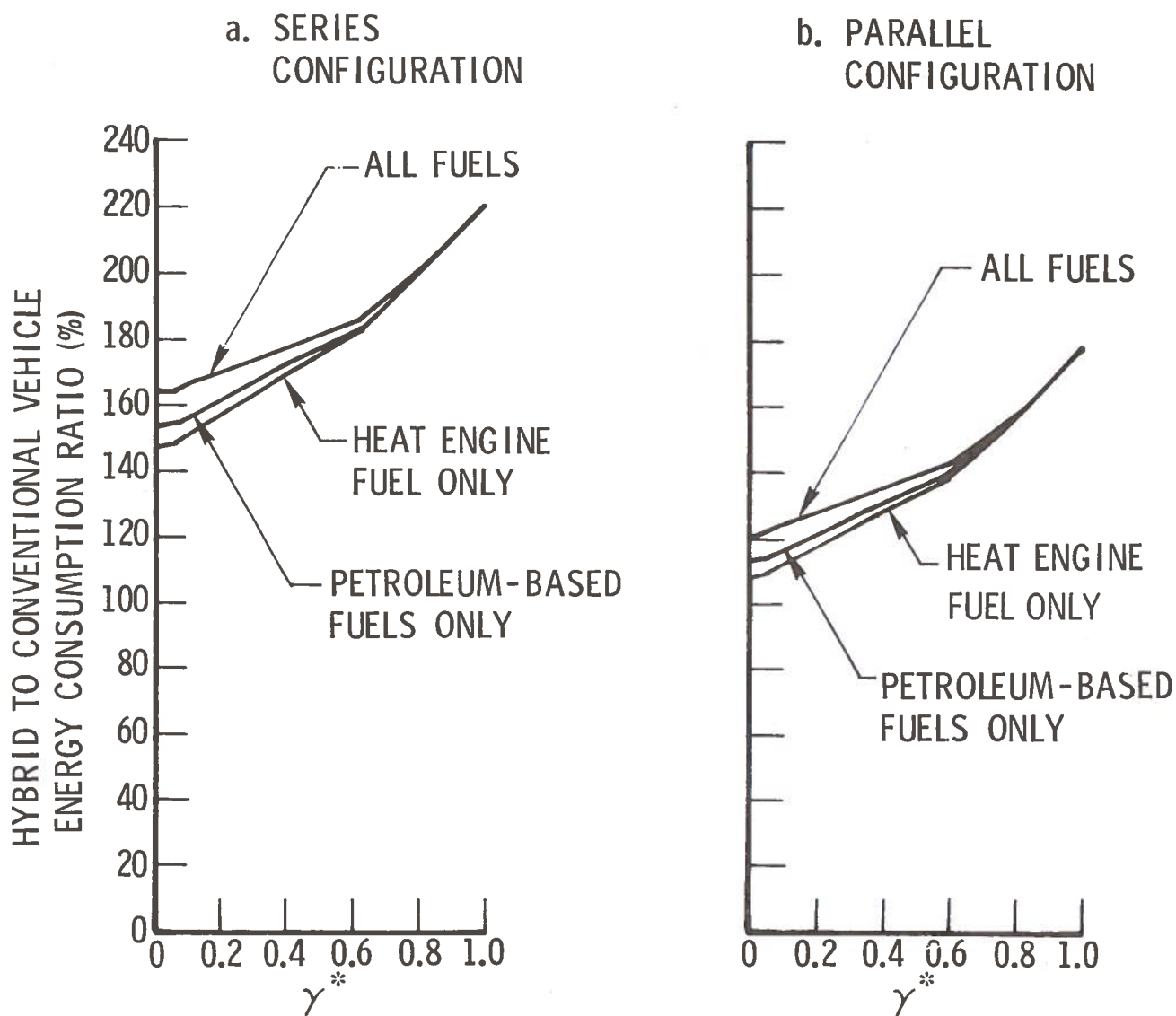
*Fraction of battery recharge energy supplied by heat engine

FIGURE 10-56. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of battery recharge energy supplied by heat engine

FIGURE 10-57. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



*Fraction of battery recharge energy supplied by heat engine

FIGURE 10-58. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

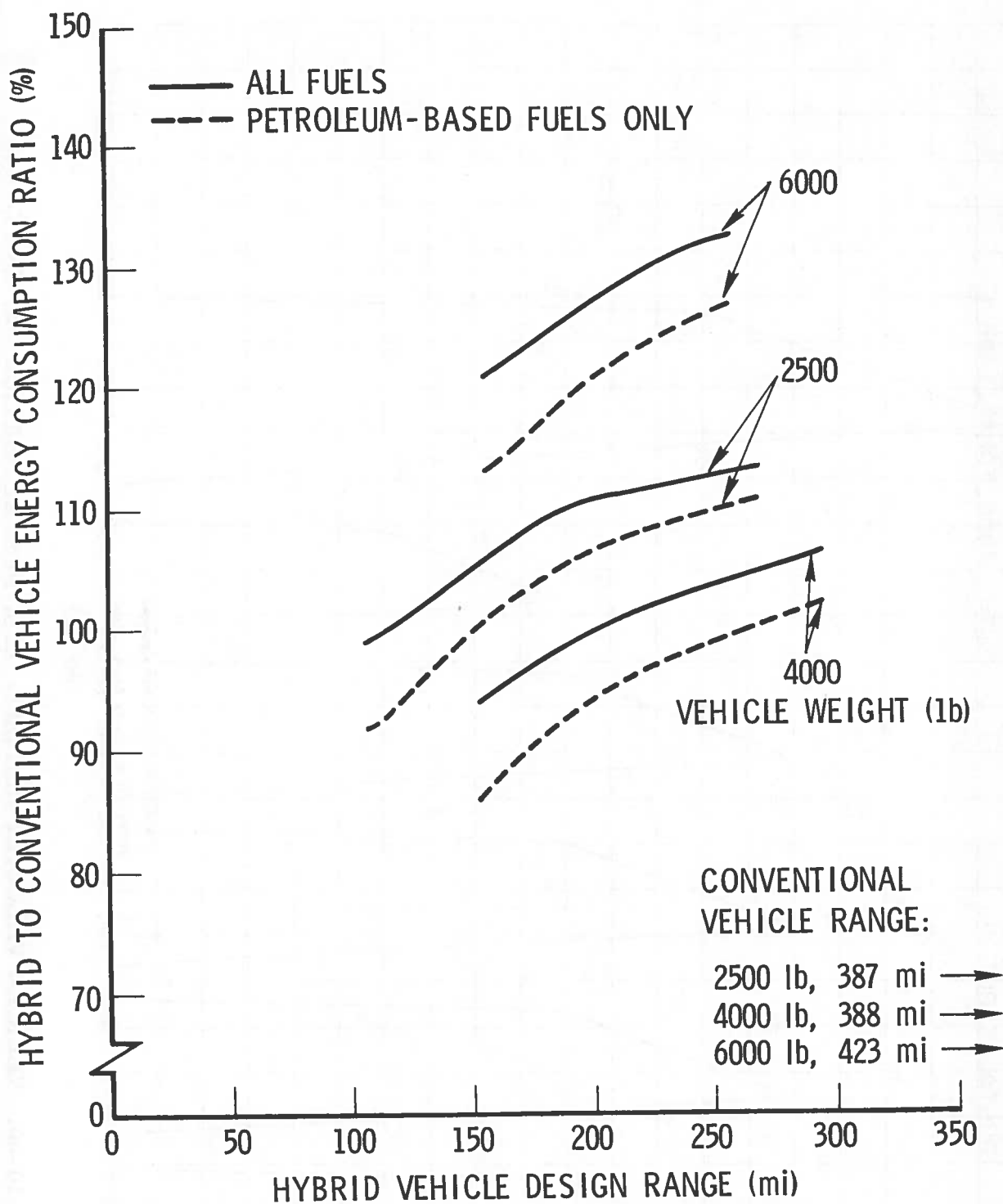


FIGURE 10-59. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: EPA HIGHWAY DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, PARALLEL CONFIGURATION

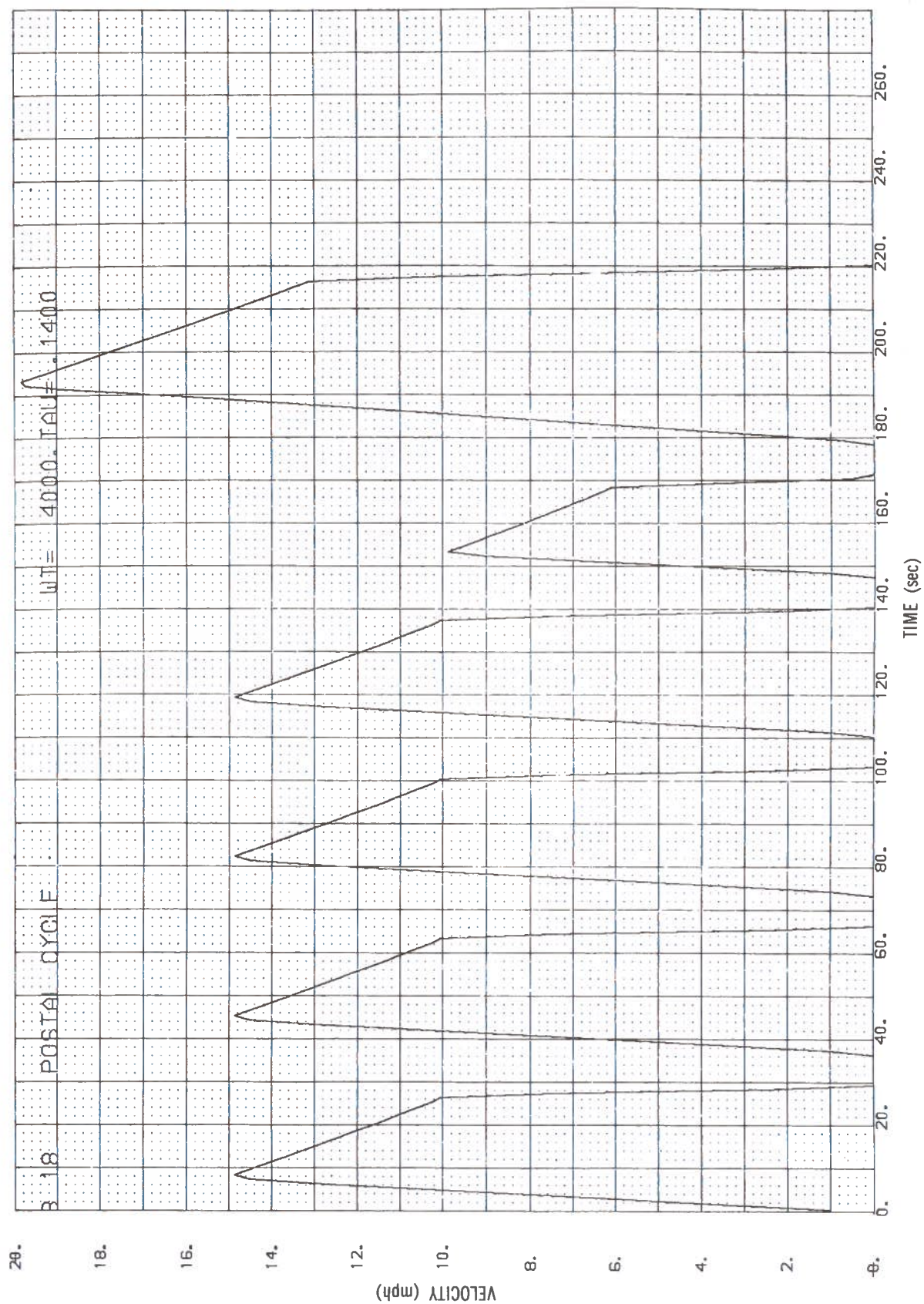


FIGURE 10-60. VEHICLE VELOCITY HISTORY: U.S. POSTAL SERVICE DRIVING CYCLE

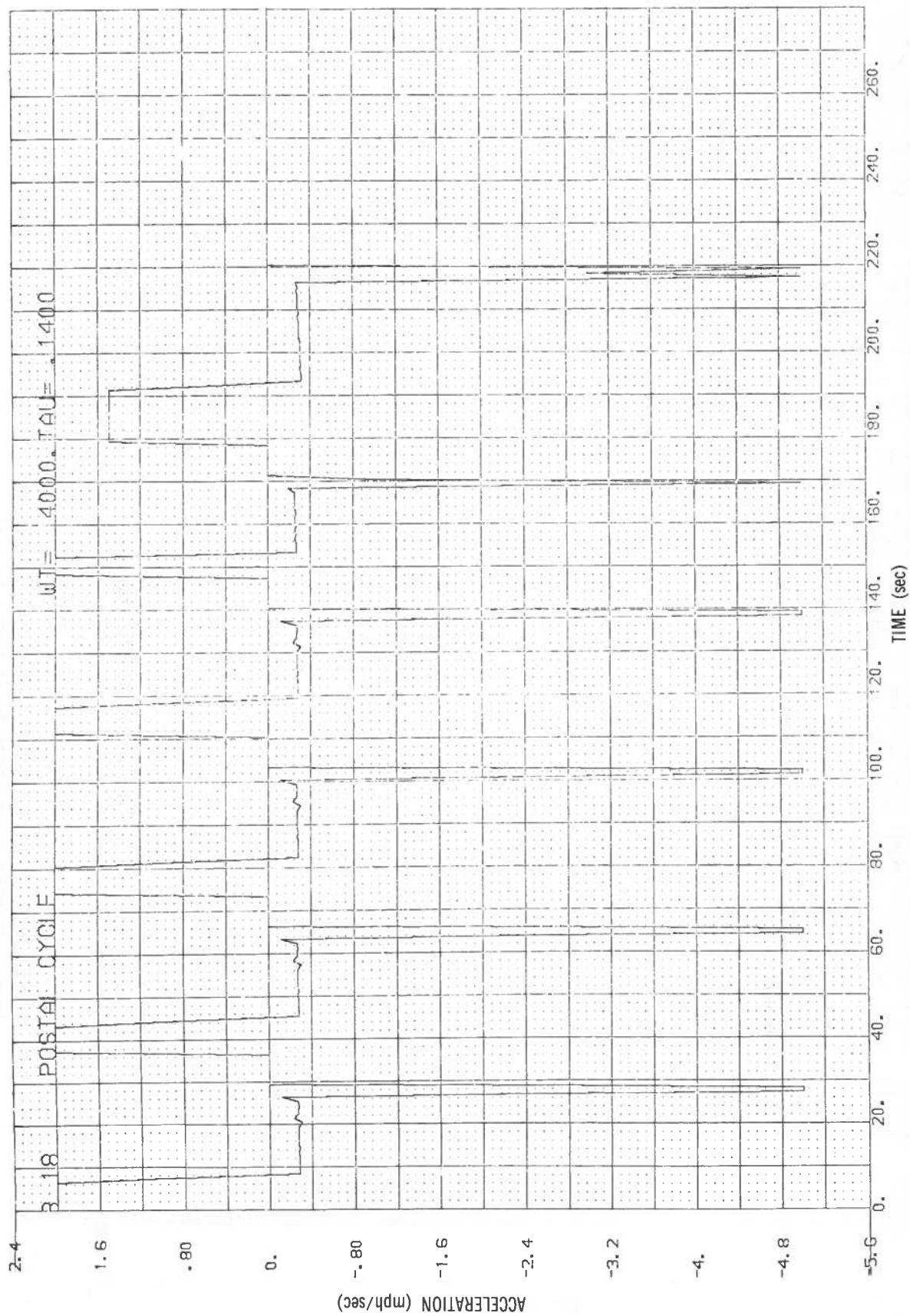


FIGURE 10-61. VEHICLE ACCELERATION HISTORY: U.S. POSTAL SERVICE DRIVING CYCLE

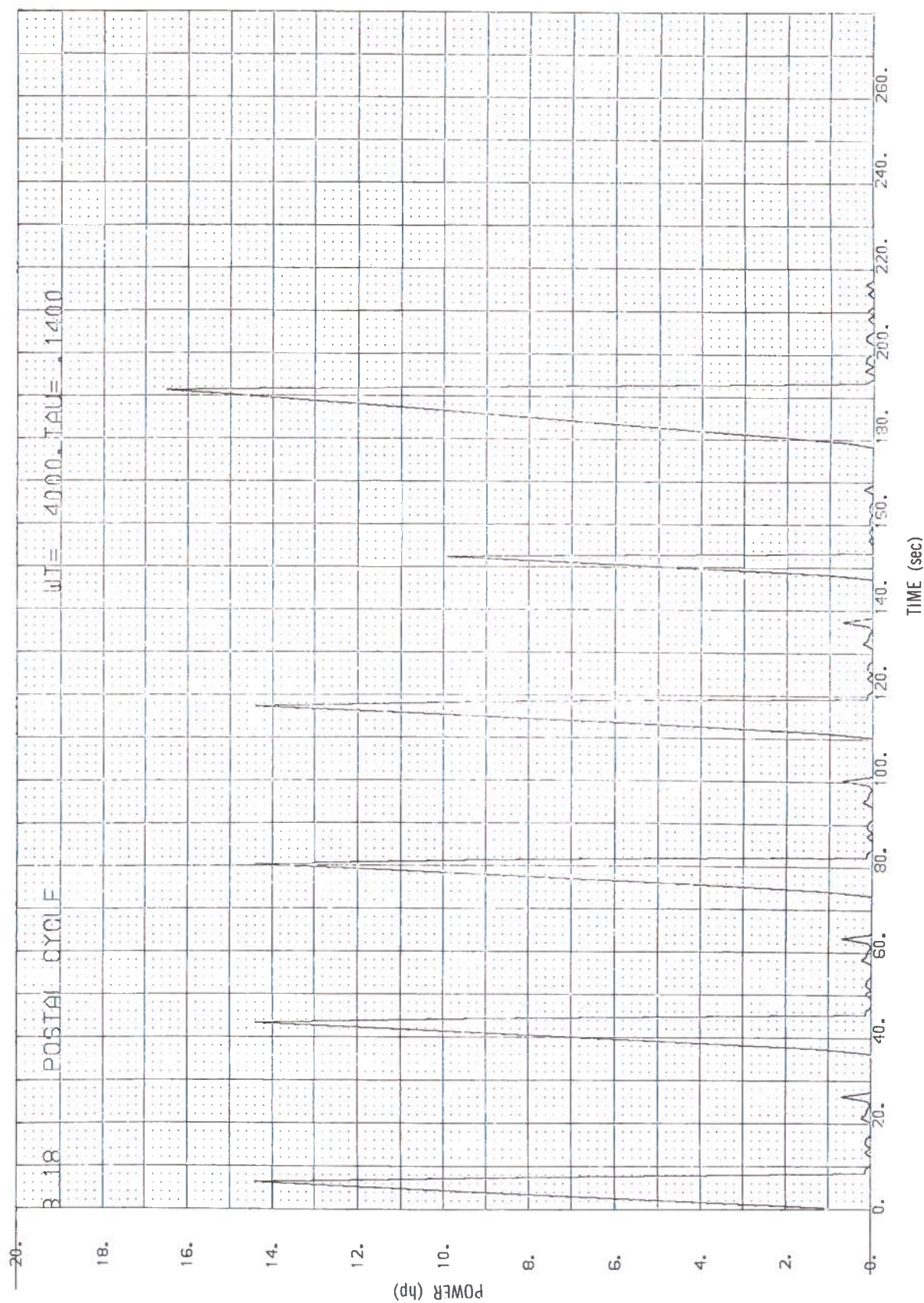


FIGURE 10-62. HISTORY OF TOTAL WHEEL POWER REQUIRED BY 4000-LB CAR ON U.S. POSTAL SERVICE DRIVING CYCLE

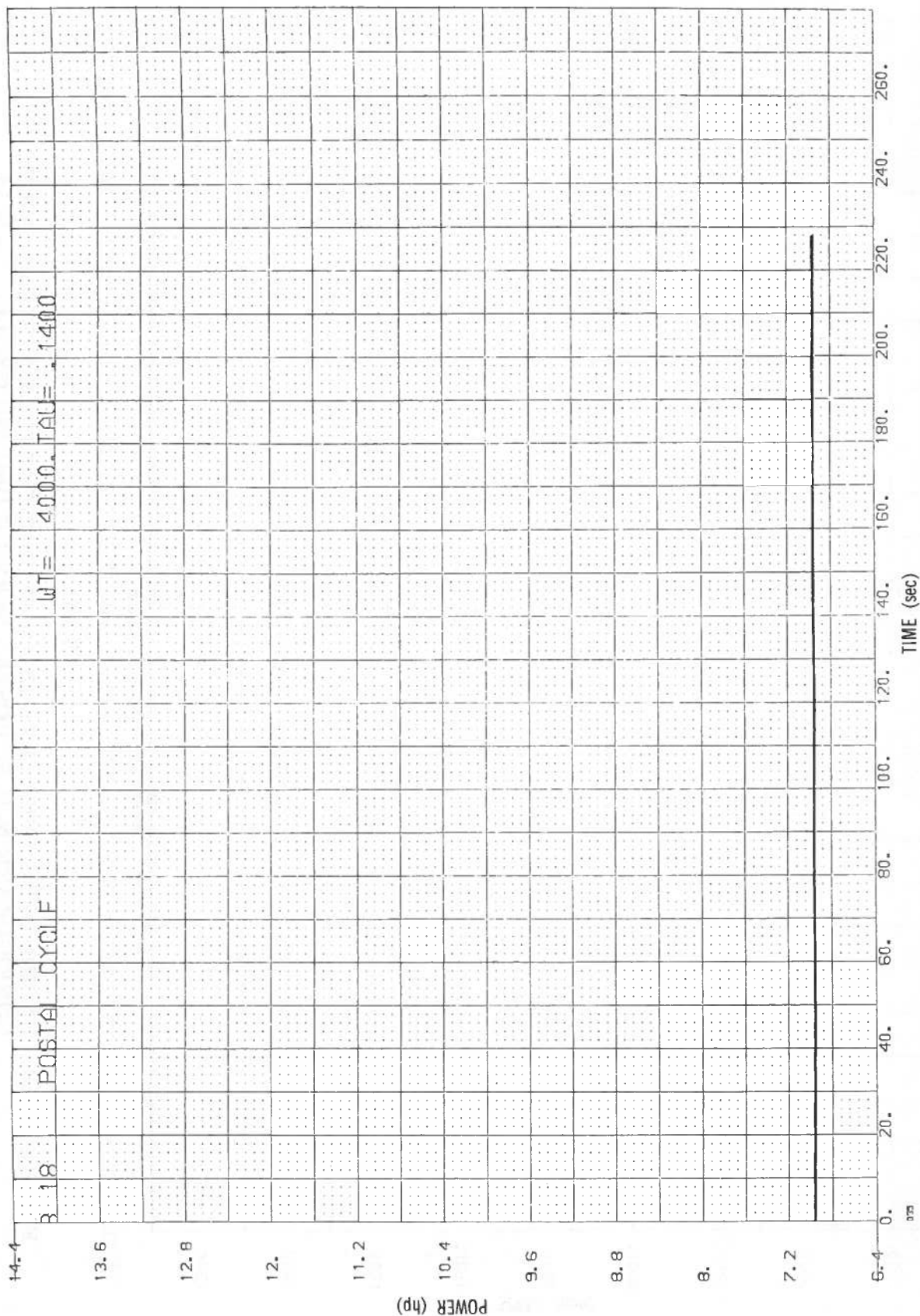


FIGURE 10-63. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, U.S. POSTAL SERVICE DRIVING CYCLE, $\tau = 0.14$

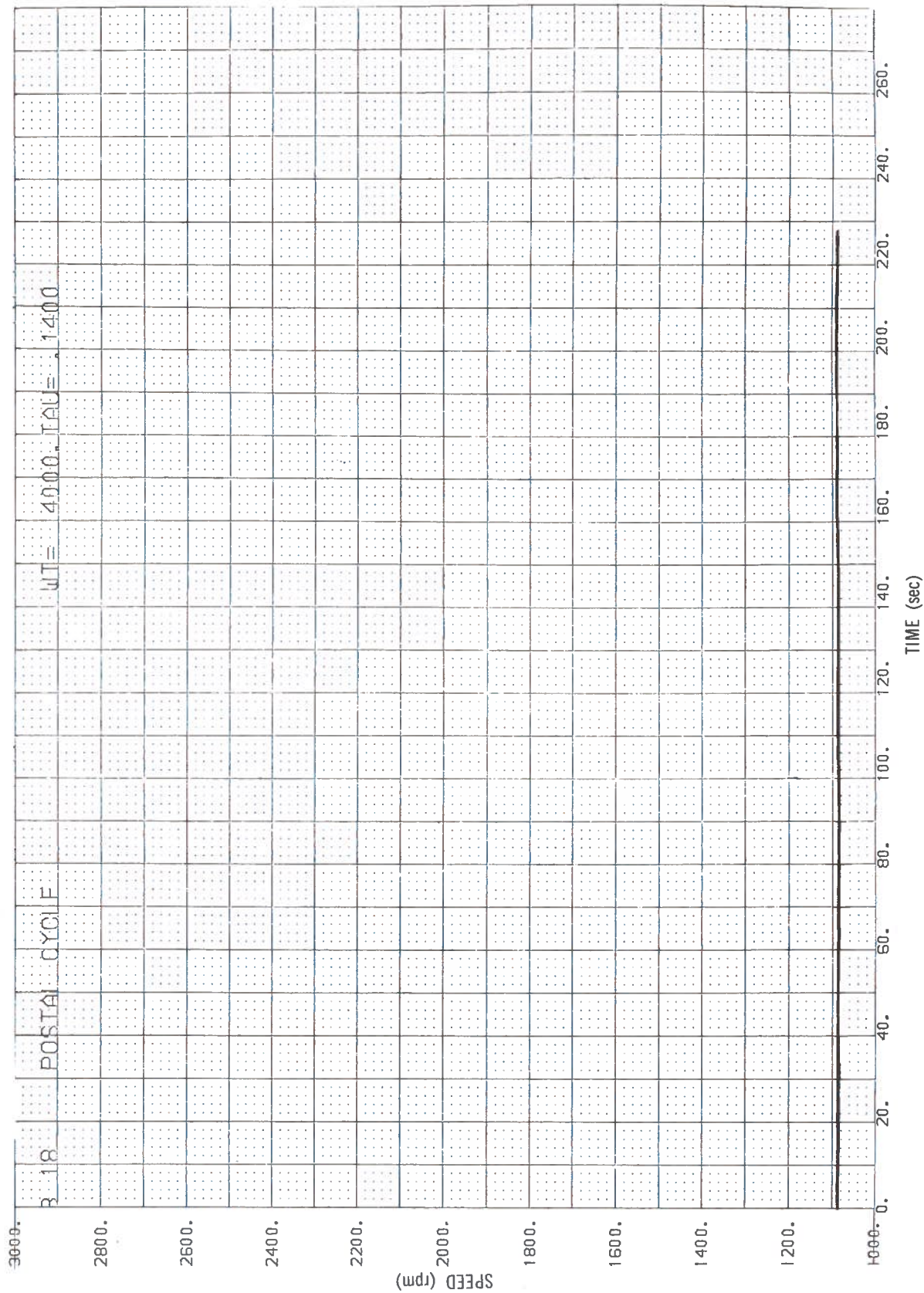


FIGURE 10-64. ENGINE SPEED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, U.S. POSTAL SERVICE DRIVING CYCLE, $\tau = 0.14$

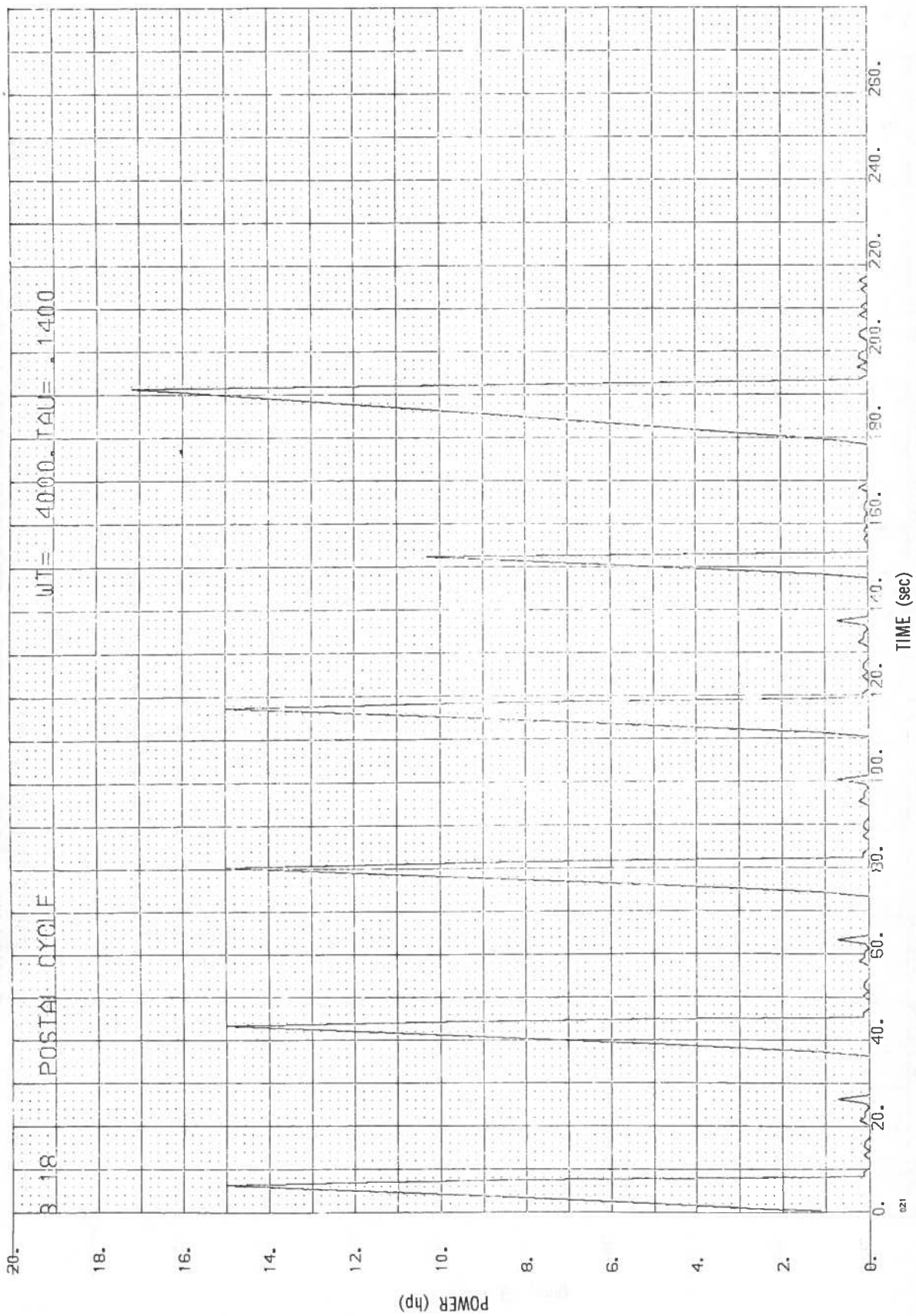


FIGURE 10-65. MOTOR POWER HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, U.S. POSTAL SERVICE DRIVING CYCLE

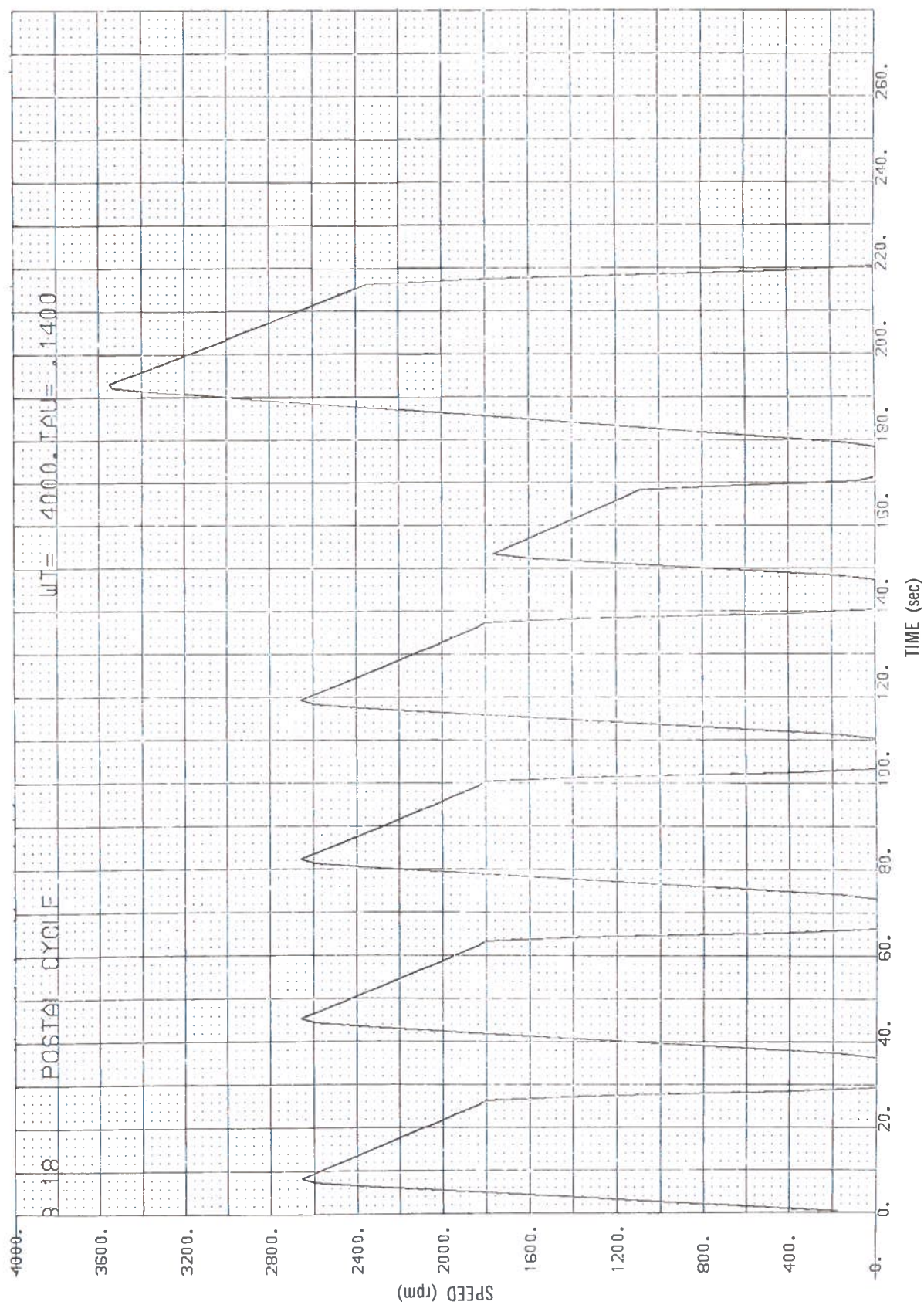


FIGURE 10-66. MOTOR SPEED HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, U.S. POSTAL SERVICE DRIVING CYCLE

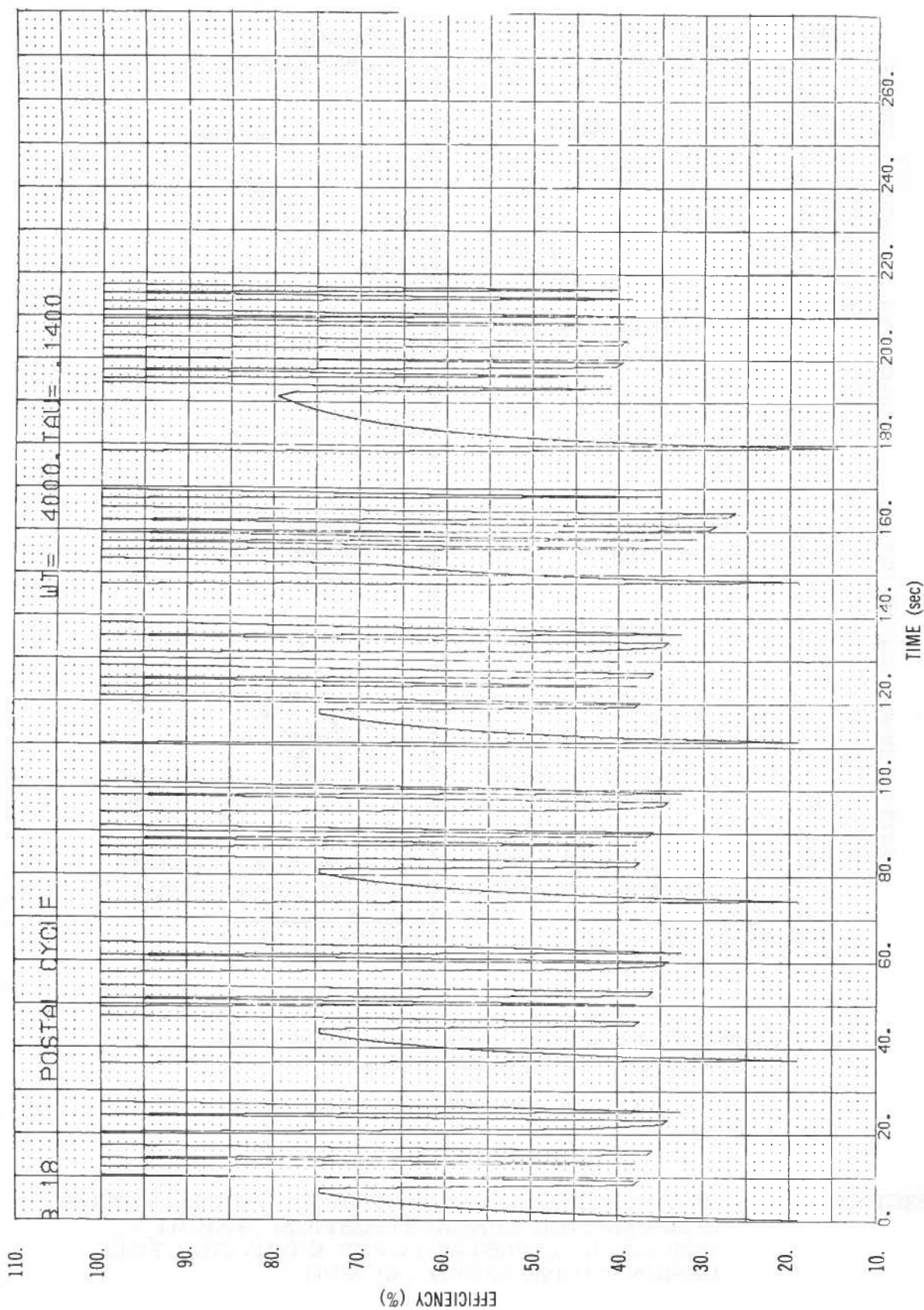
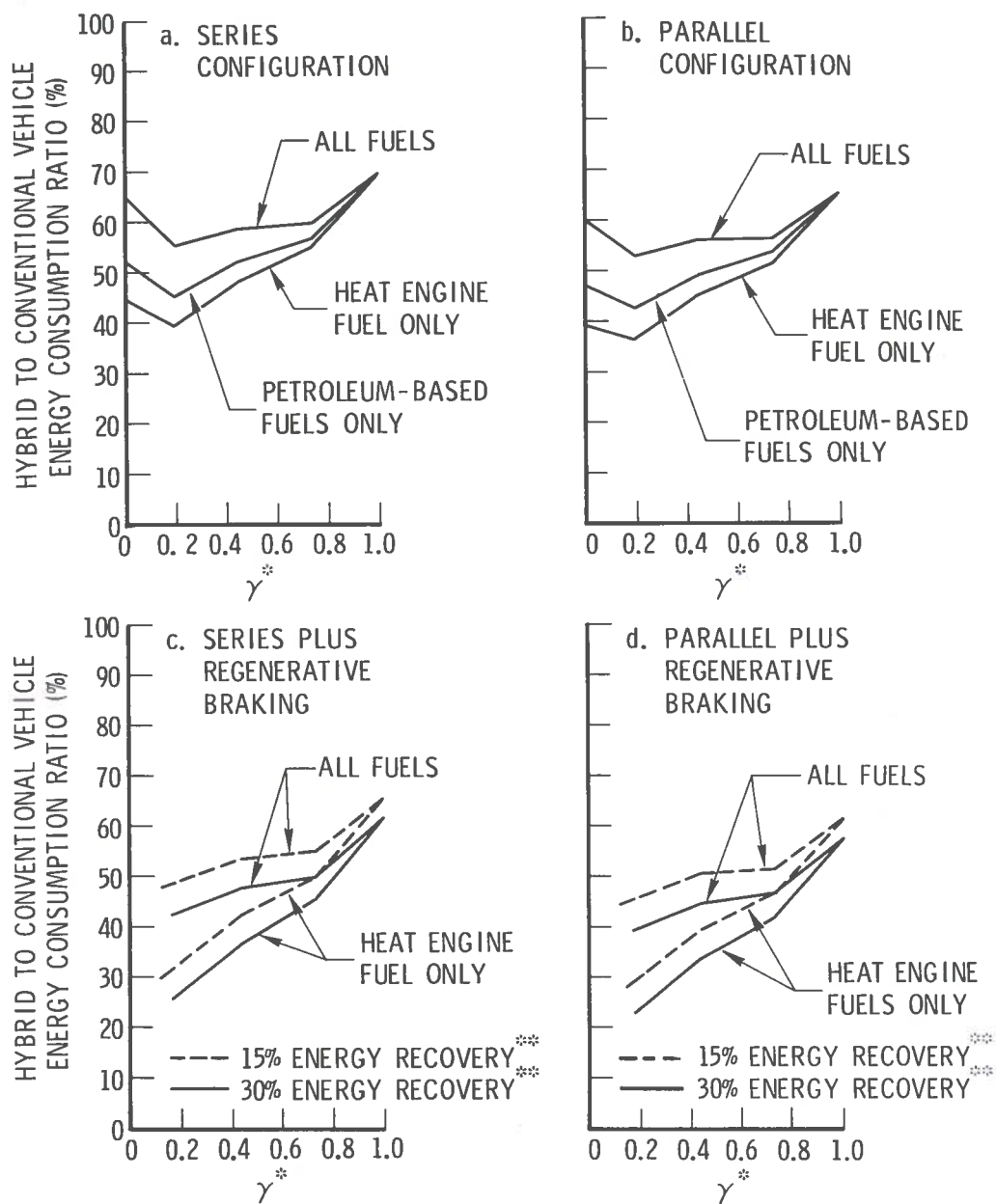


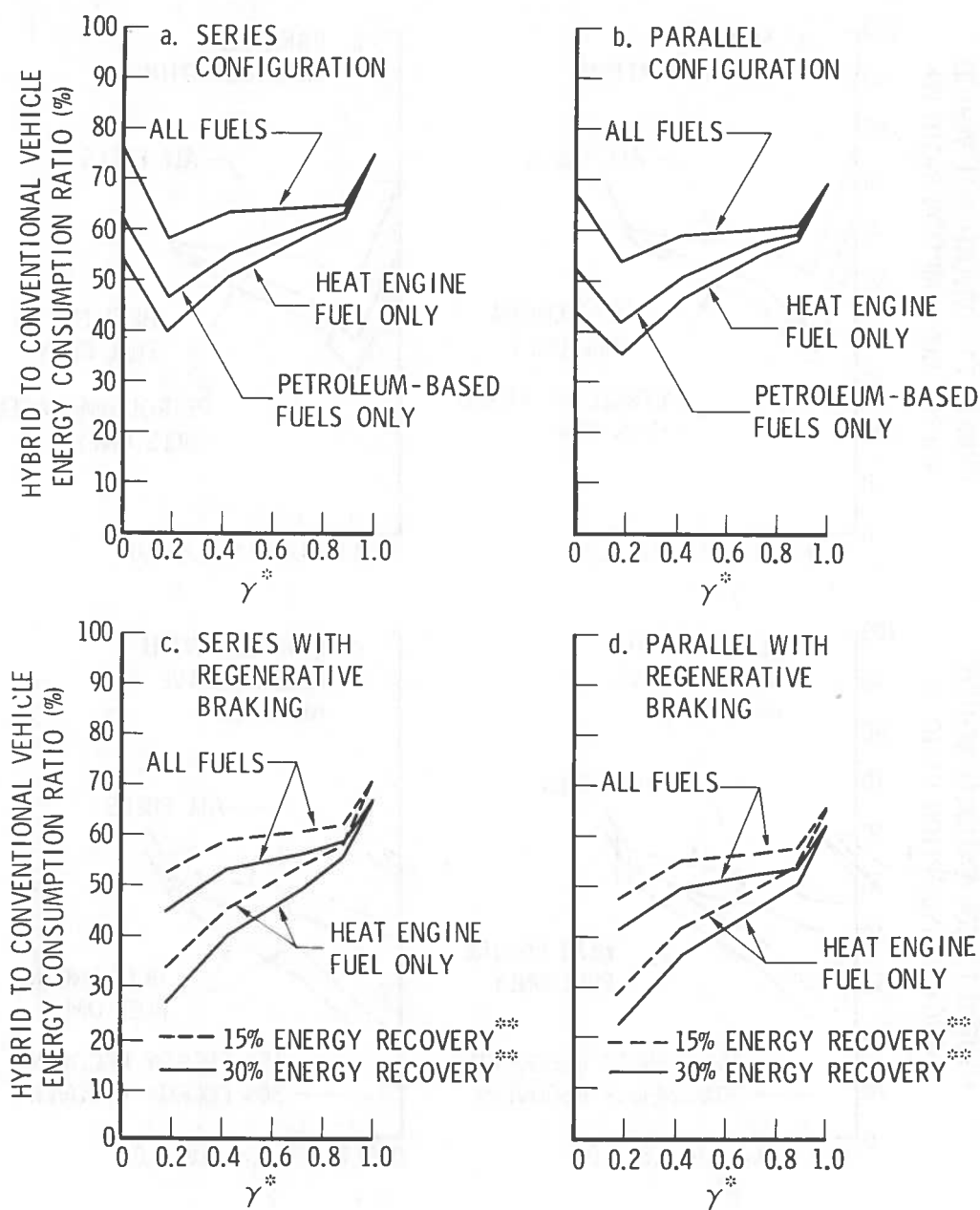
FIGURE 10-67. MOTOR EFFICIENCY HISTORY: HEAT ENGINE/BATTERY SYSTEM, SERIES CONFIGURATION, U.S. POSTAL SERVICE DRIVING CYCLE



* 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

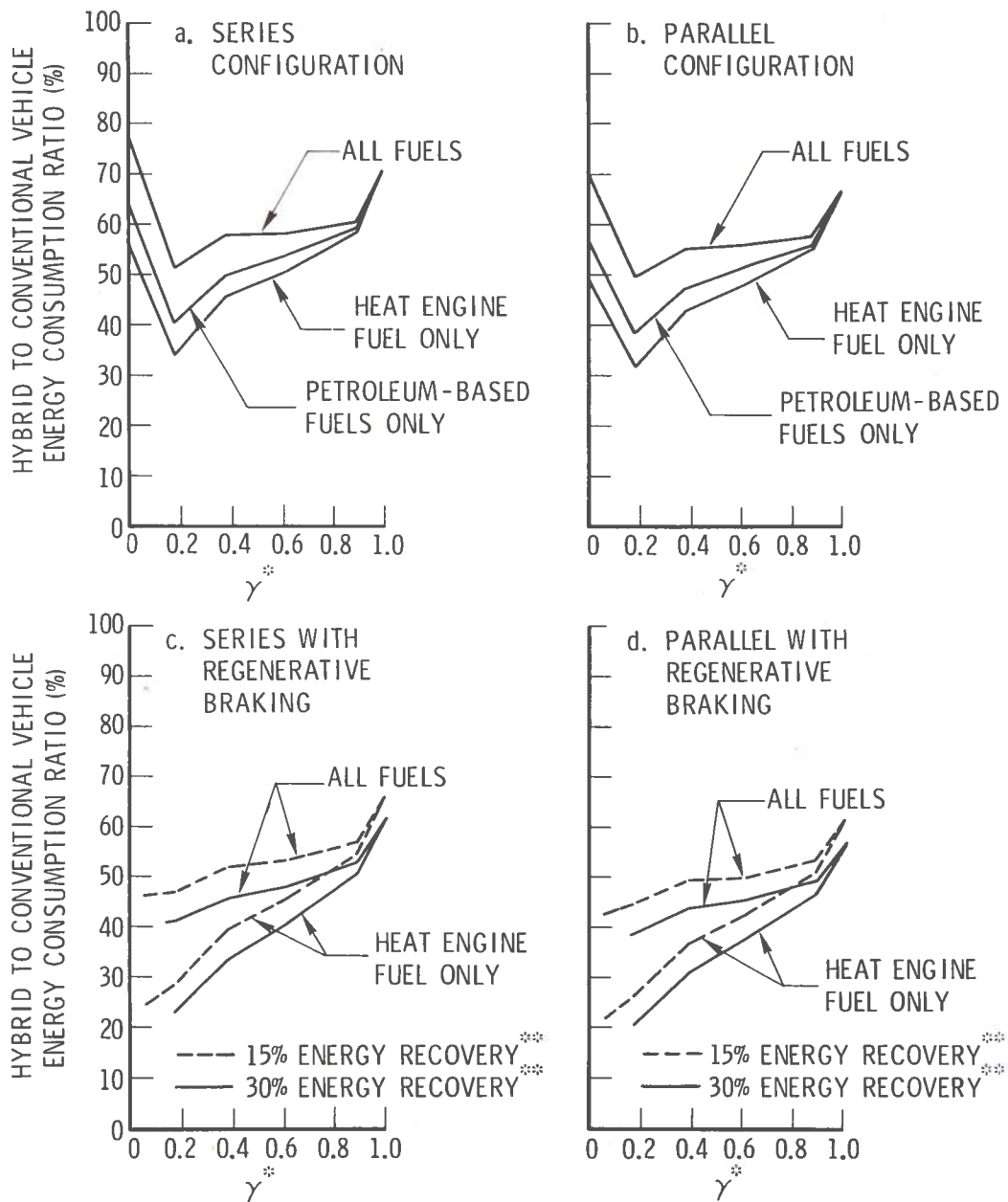
FIGURE 10-68. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



* 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 10-69. 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 10-70. HEAT ENGINE/BATTERY HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

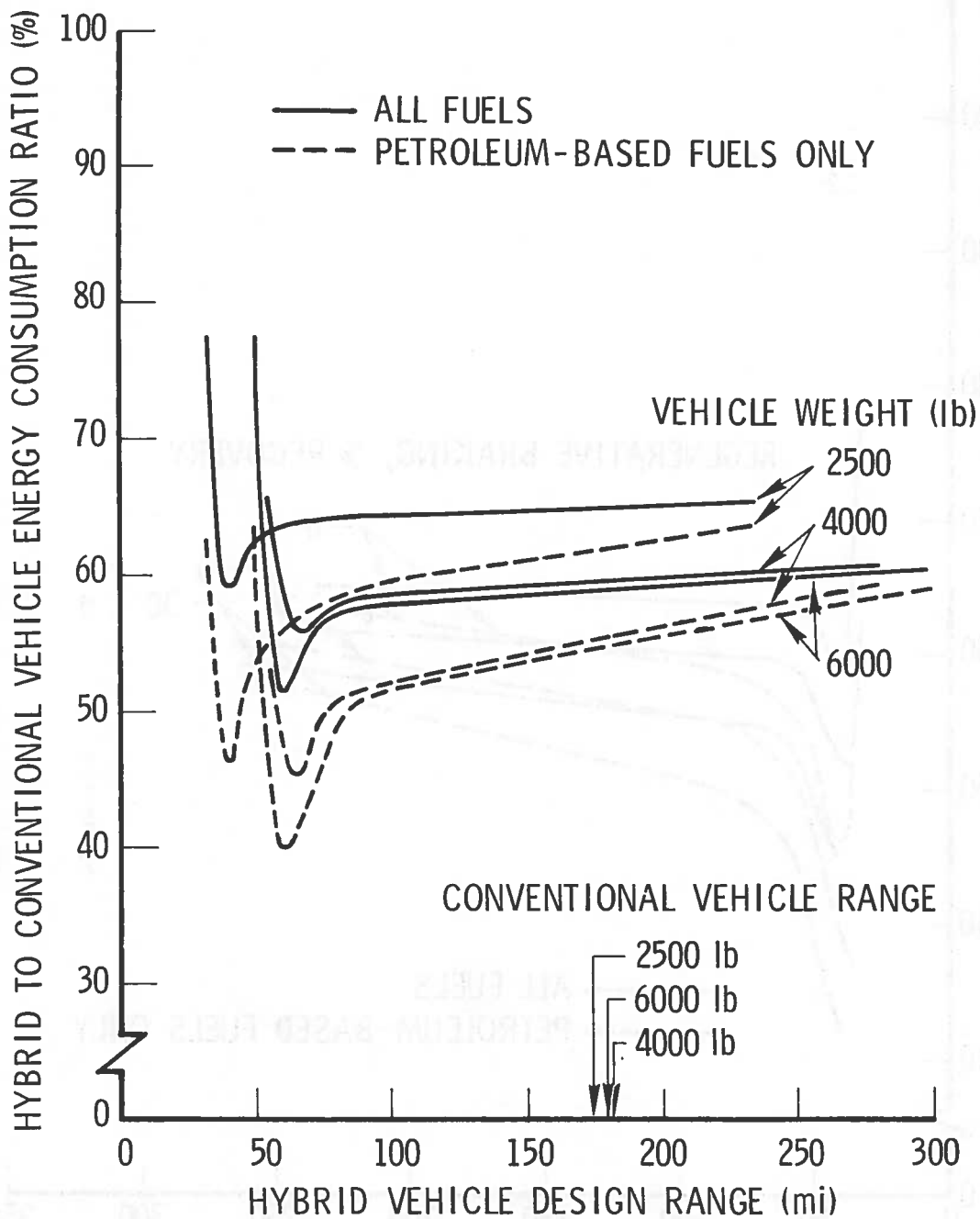


FIGURE 10-71. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION

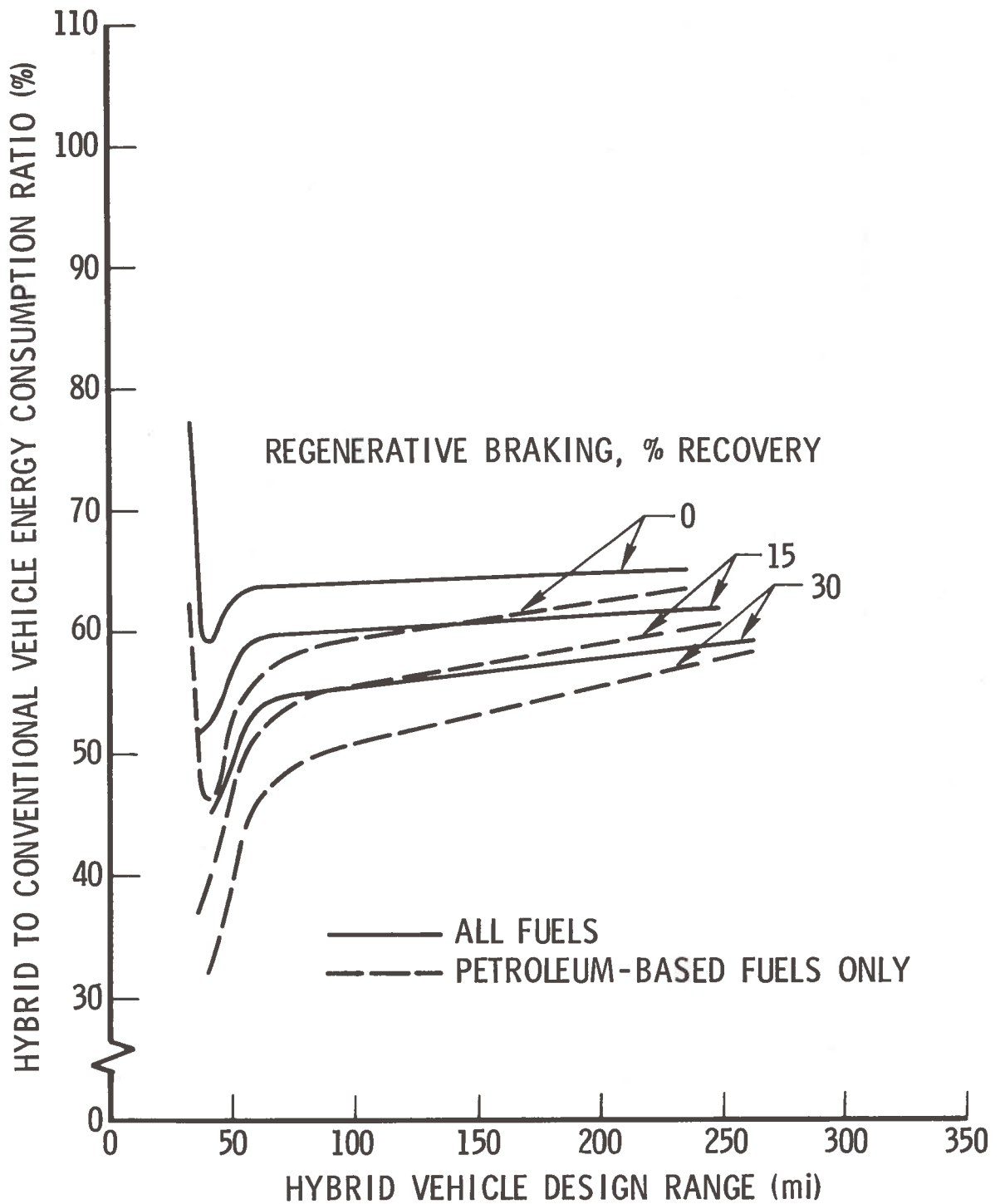


FIGURE 10-72. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, SERIES CONFIGURATION

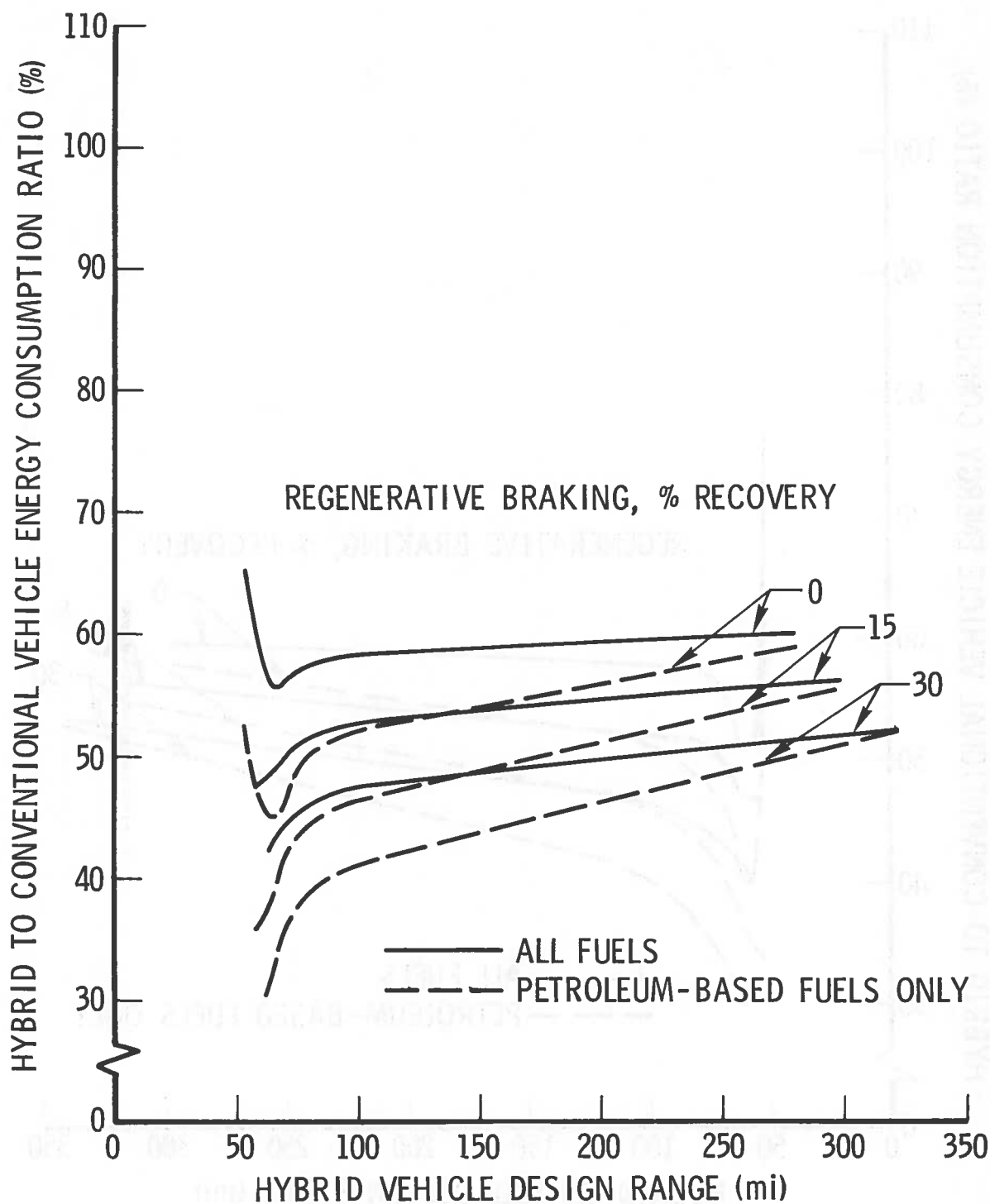


FIGURE 10-73. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, SERIES CONFIGURATION

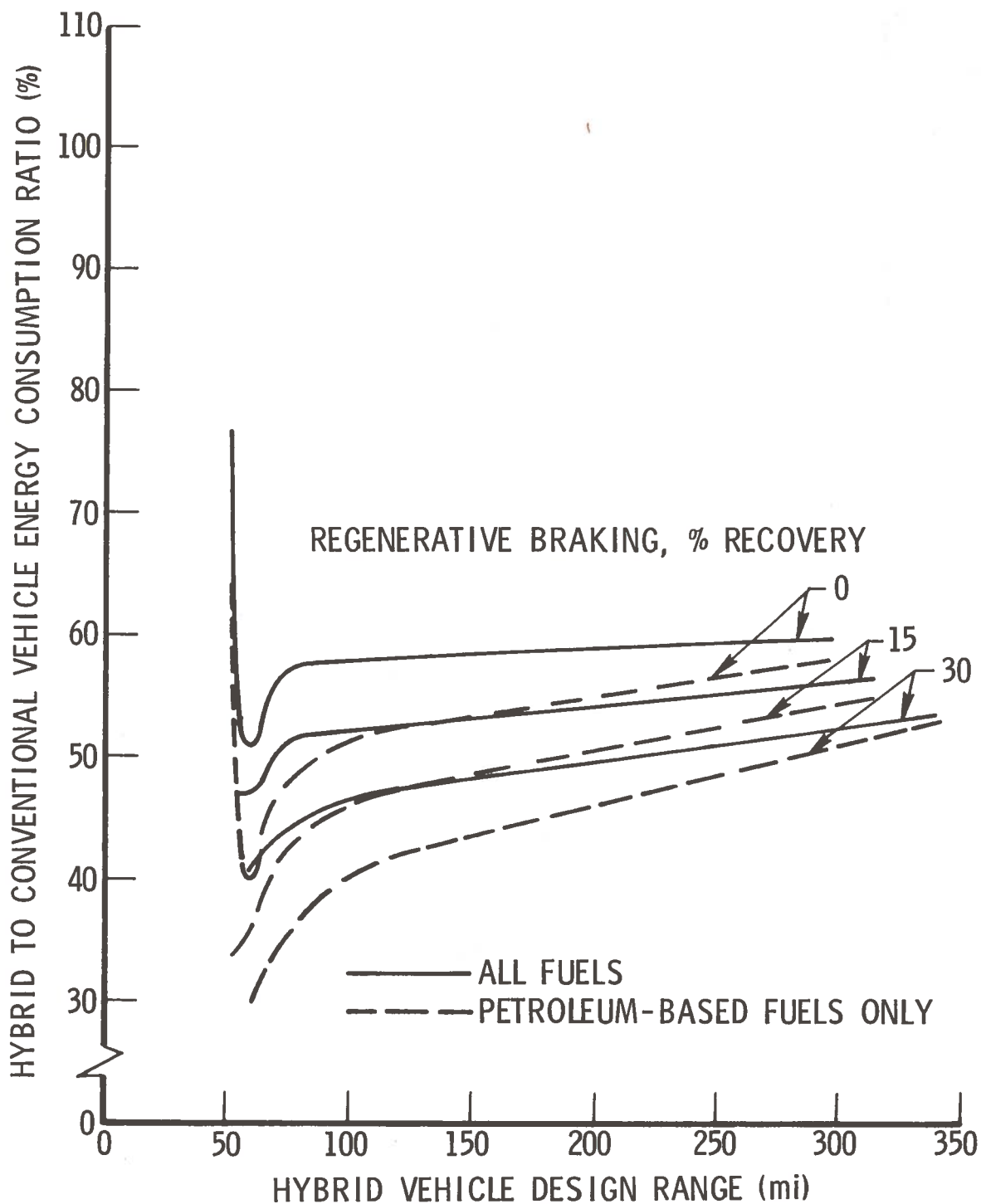


FIGURE 10-74. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, SERIES CONFIGURATION

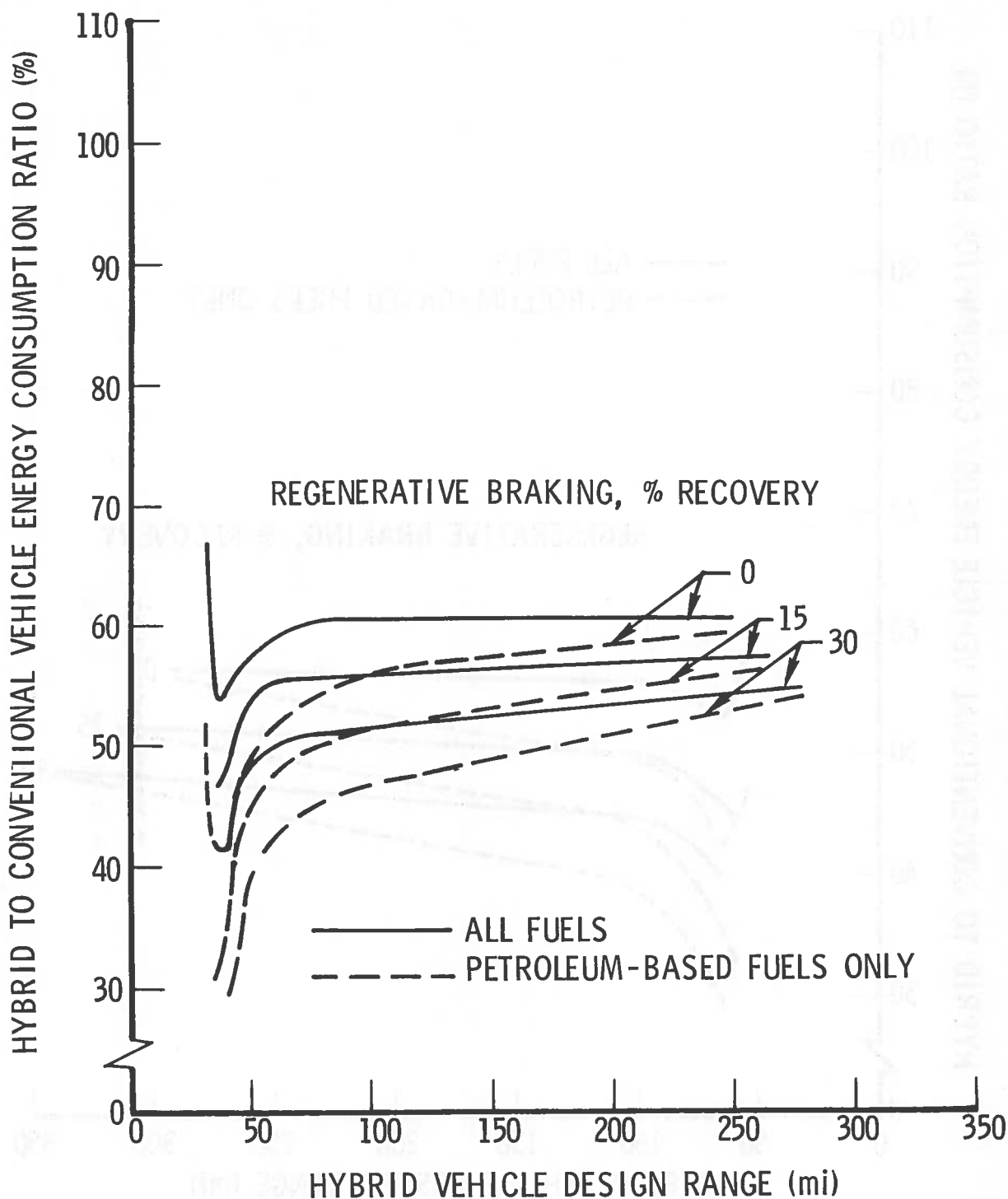


FIGURE 10-75. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 2500-LB CAR, PARALLEL CONFIGURATION

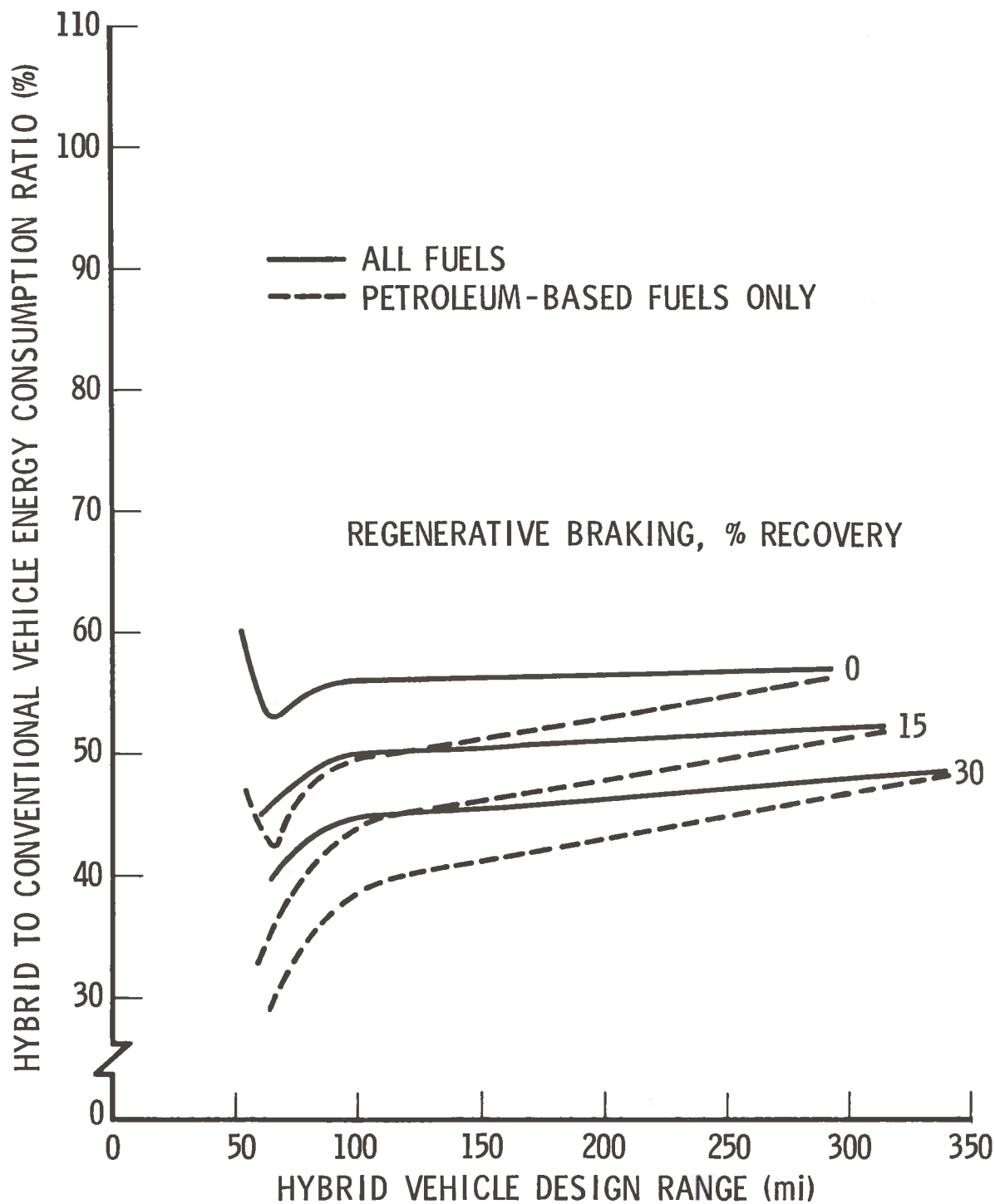


FIGURE 10-76. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 4000-LB CAR, PARALLEL CONFIGURATION

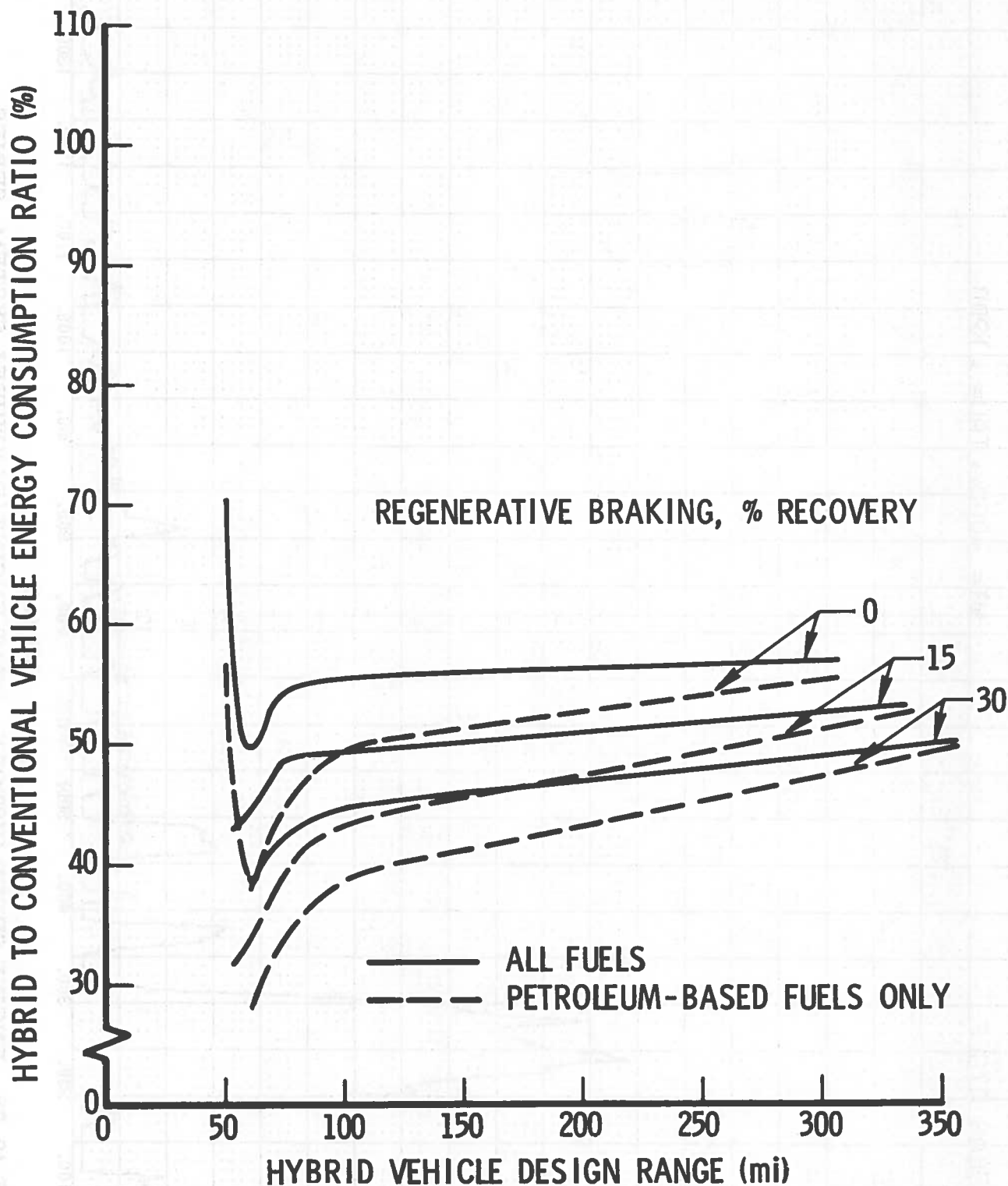


FIGURE 10-77. HYBRID HEAT ENGINE/BATTERY VEHICLE-RELATED ENERGY CONSUMPTION: U.S. POSTAL SERVICE DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, 6000-LB VAN, PARALLEL CONFIGURATION

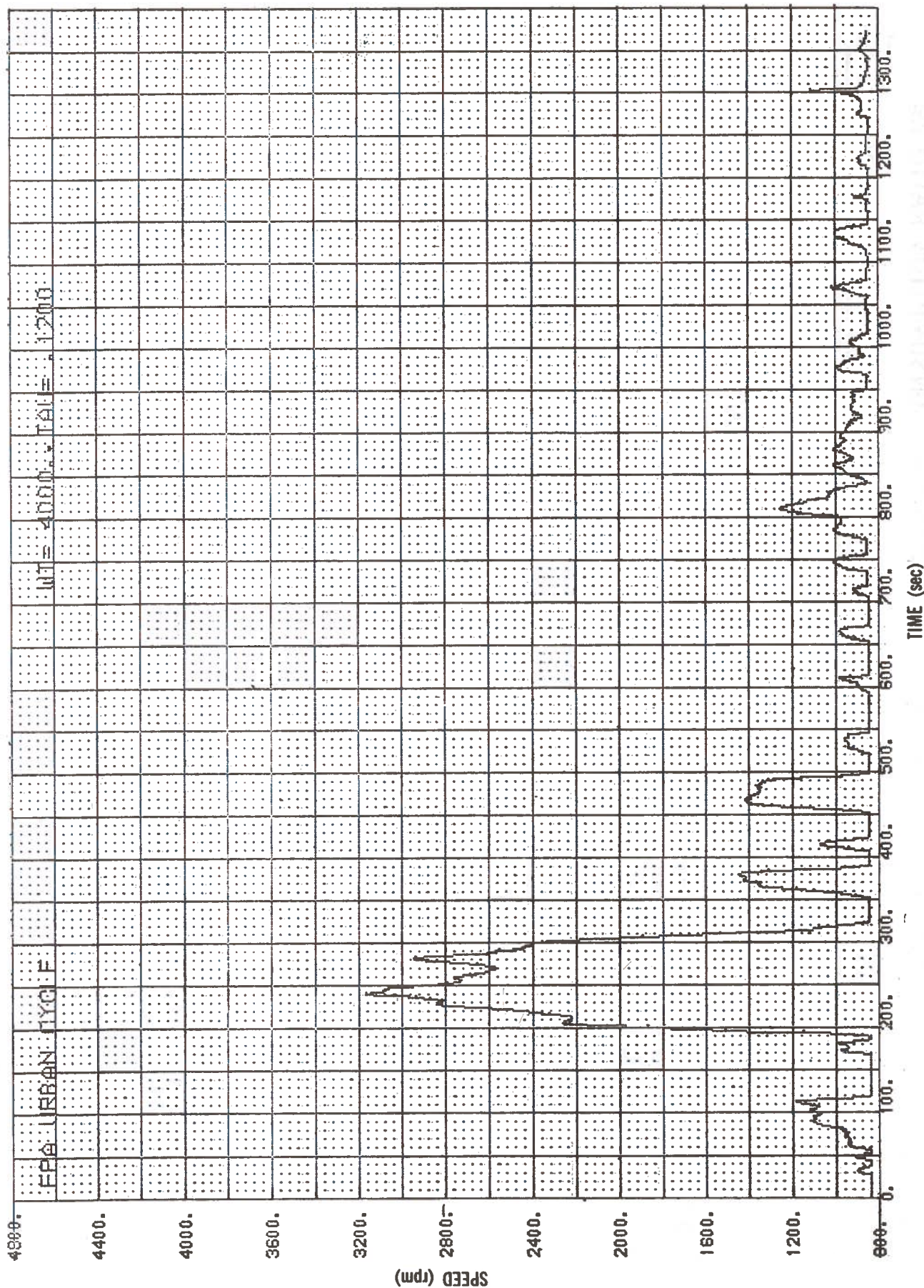


FIGURE 10-78. ENGINE SPEED HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

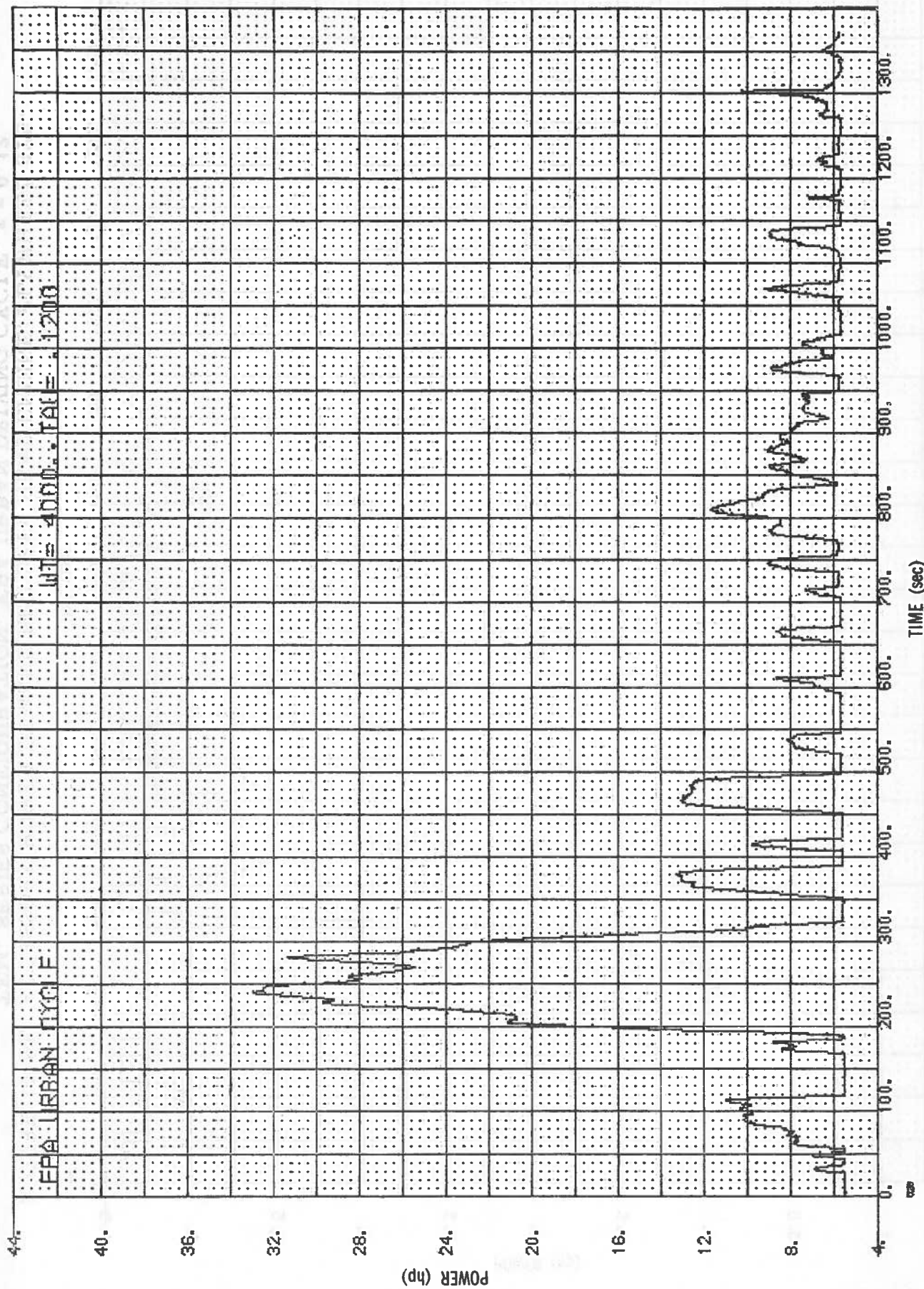


FIGURE 10-79. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

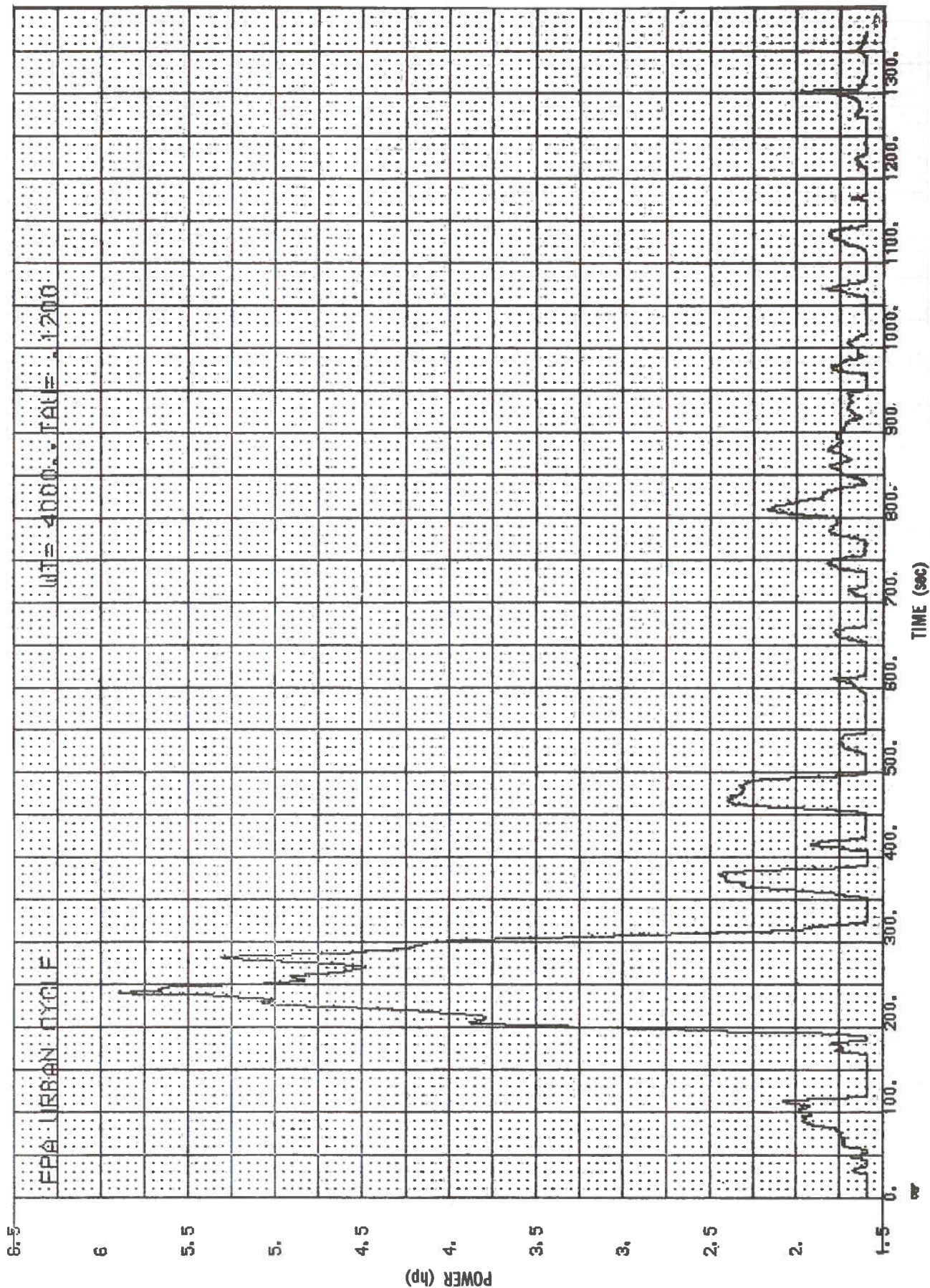


FIGURE 10-80. ACCESSORY POWER DEMAND HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

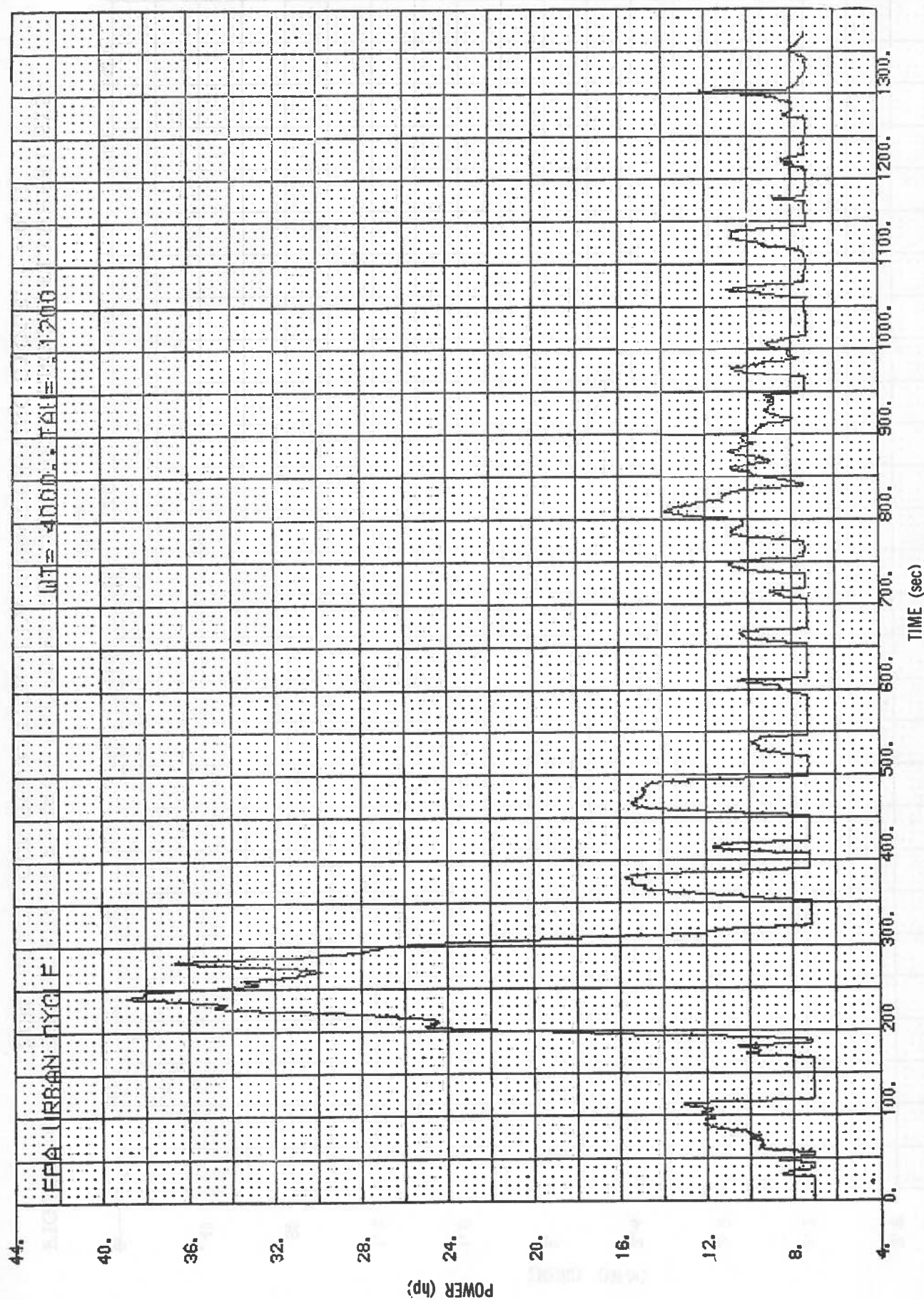


FIGURE 10-81. ENGINE TOTAL POWER OUTPUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

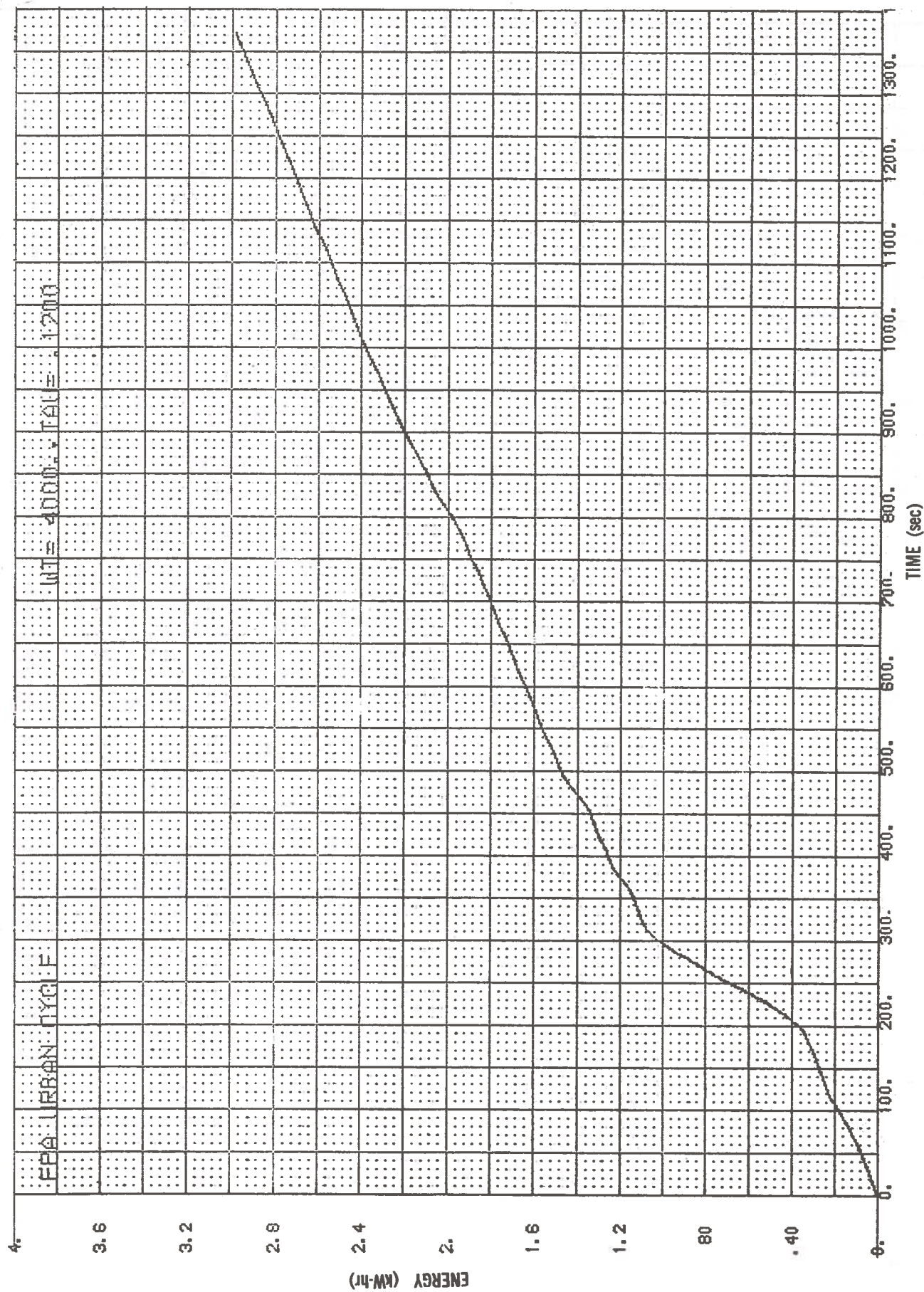


FIGURE 10-82. ENGINE SHAFT ENERGY PROVIDED HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

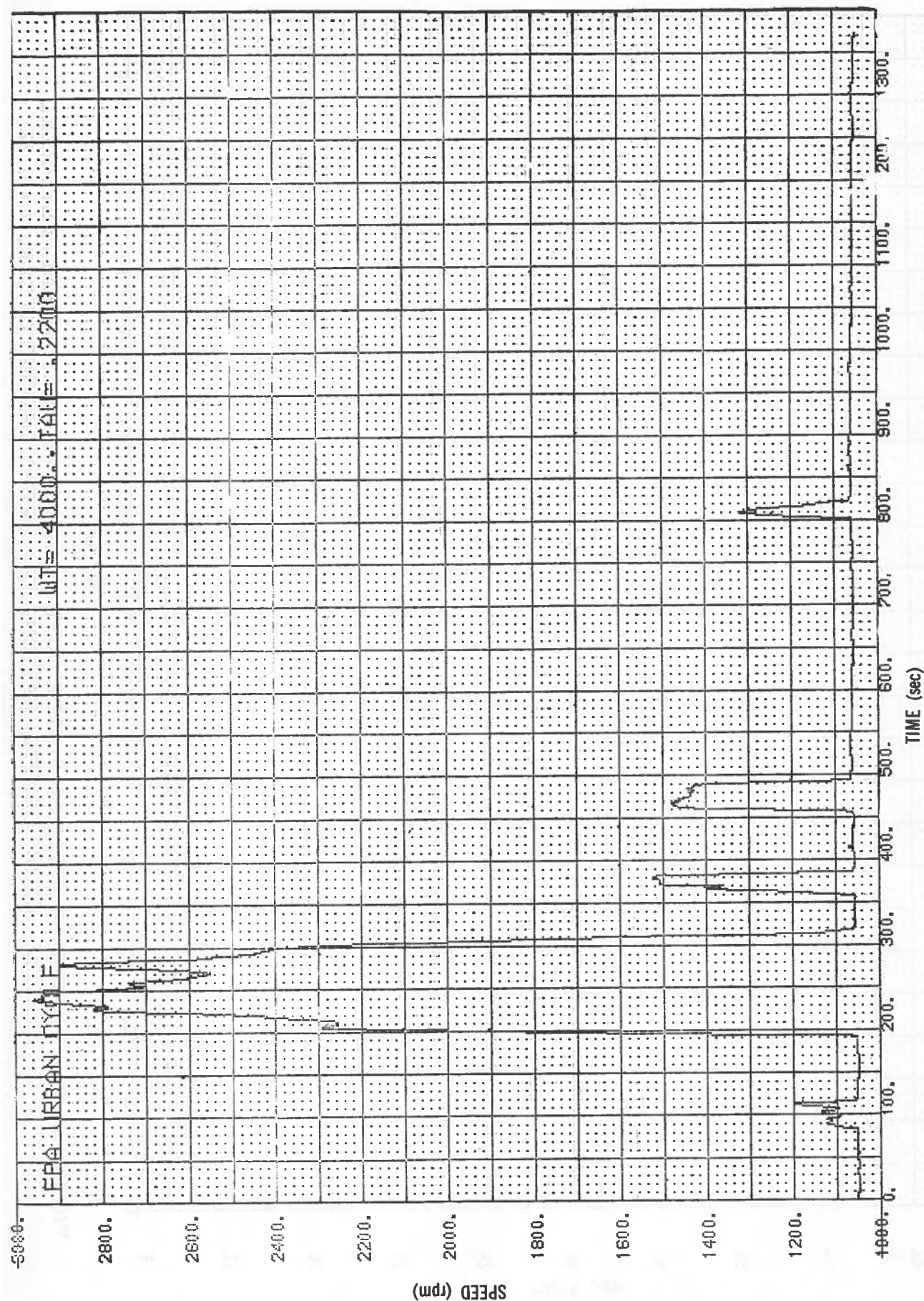


FIGURE 10-83. ENGINE SPEED HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIE
CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

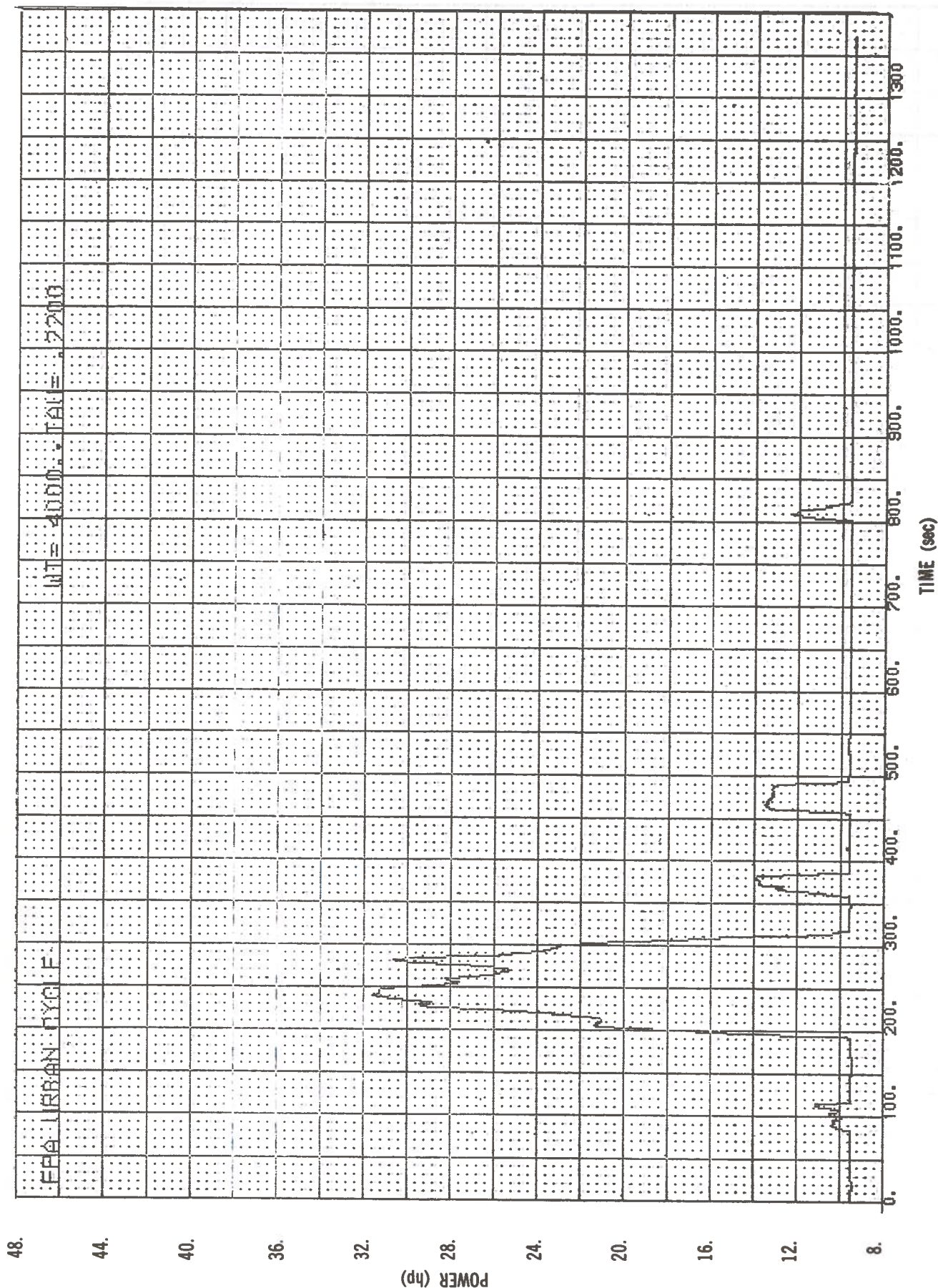


FIGURE 10-84. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

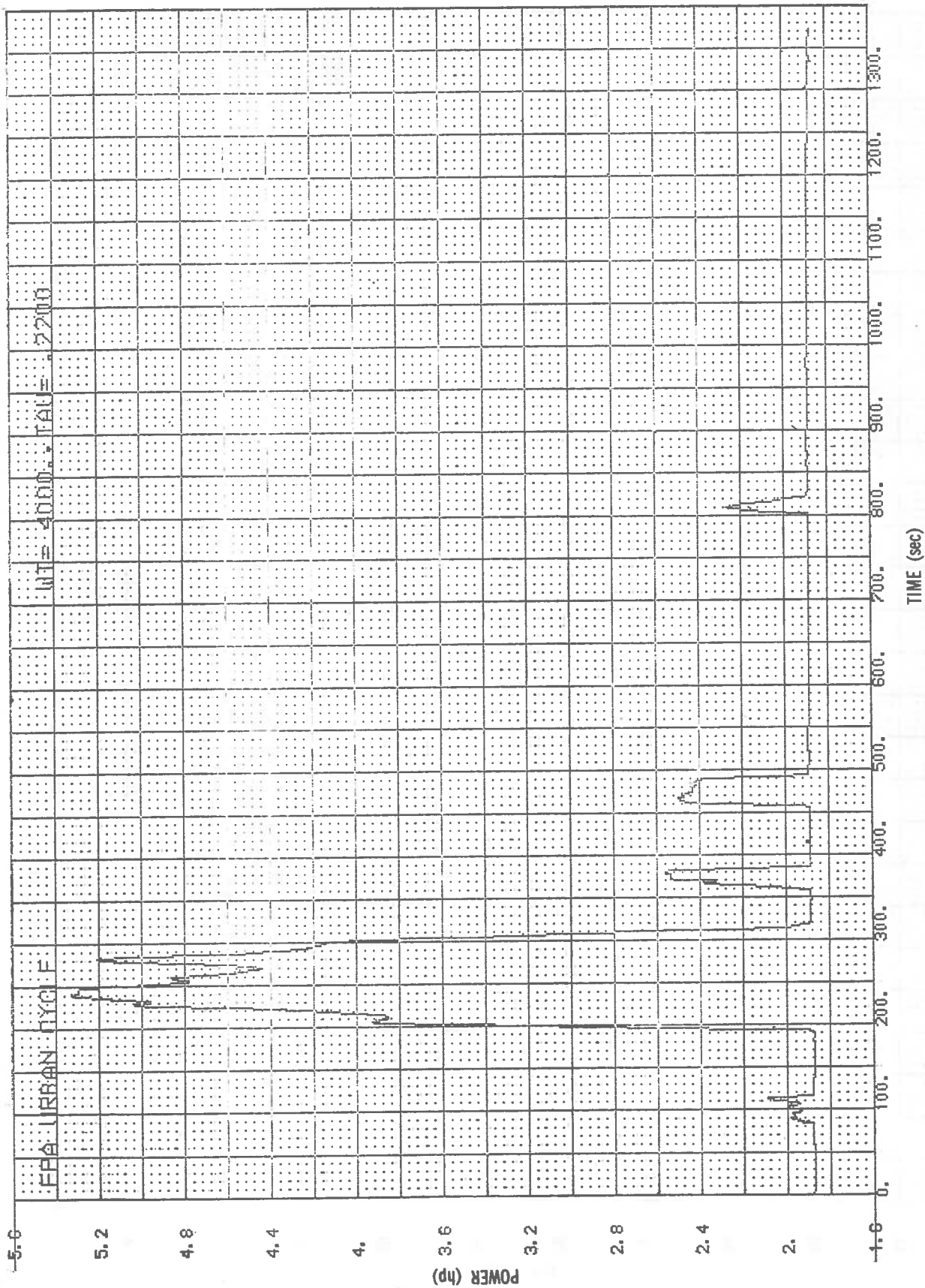


FIGURE 10-85. ACCESSORY POWER DEMAND HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

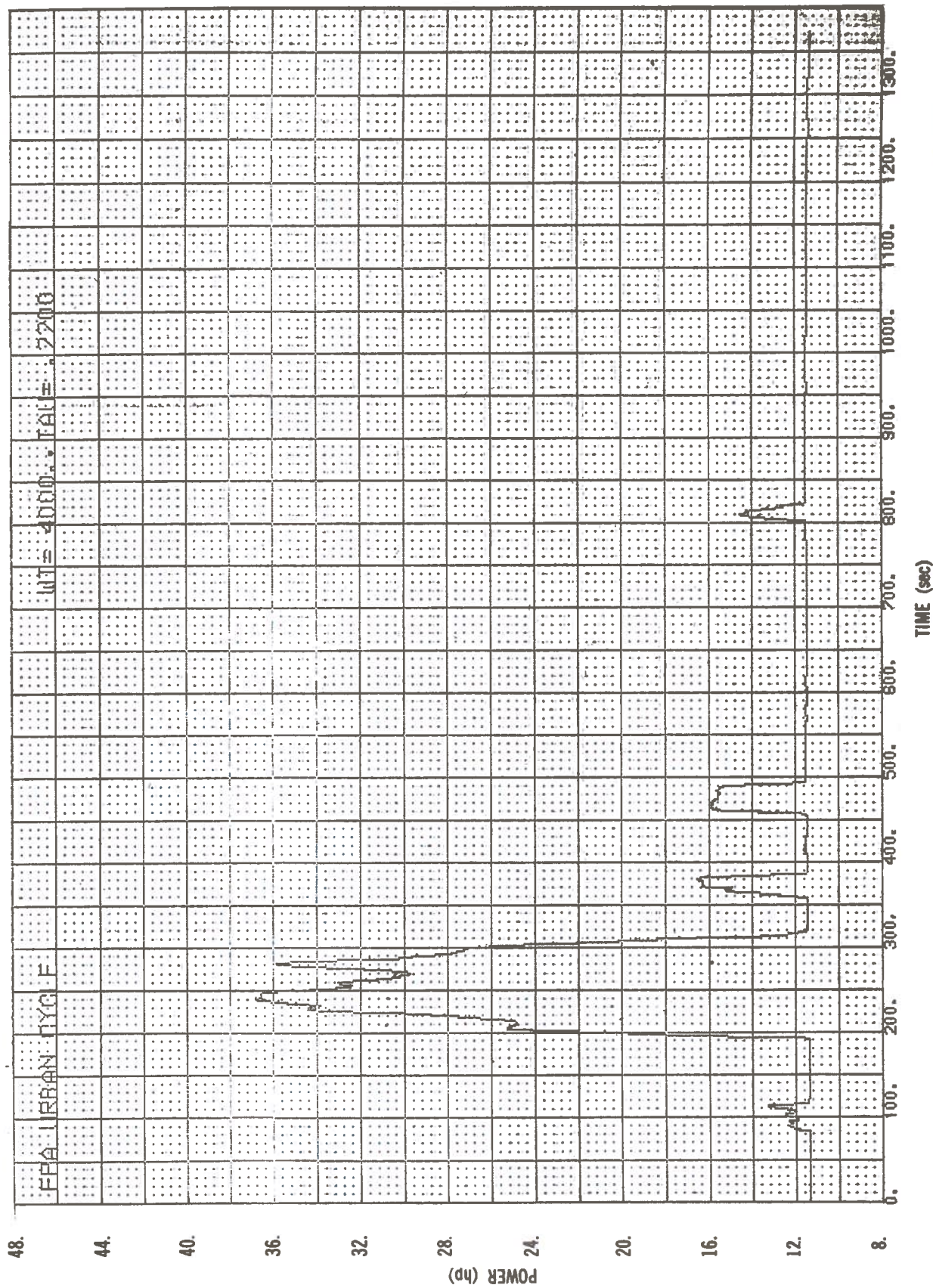


FIGURE 10-86. ENGINE TOTAL POWER OUTPUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

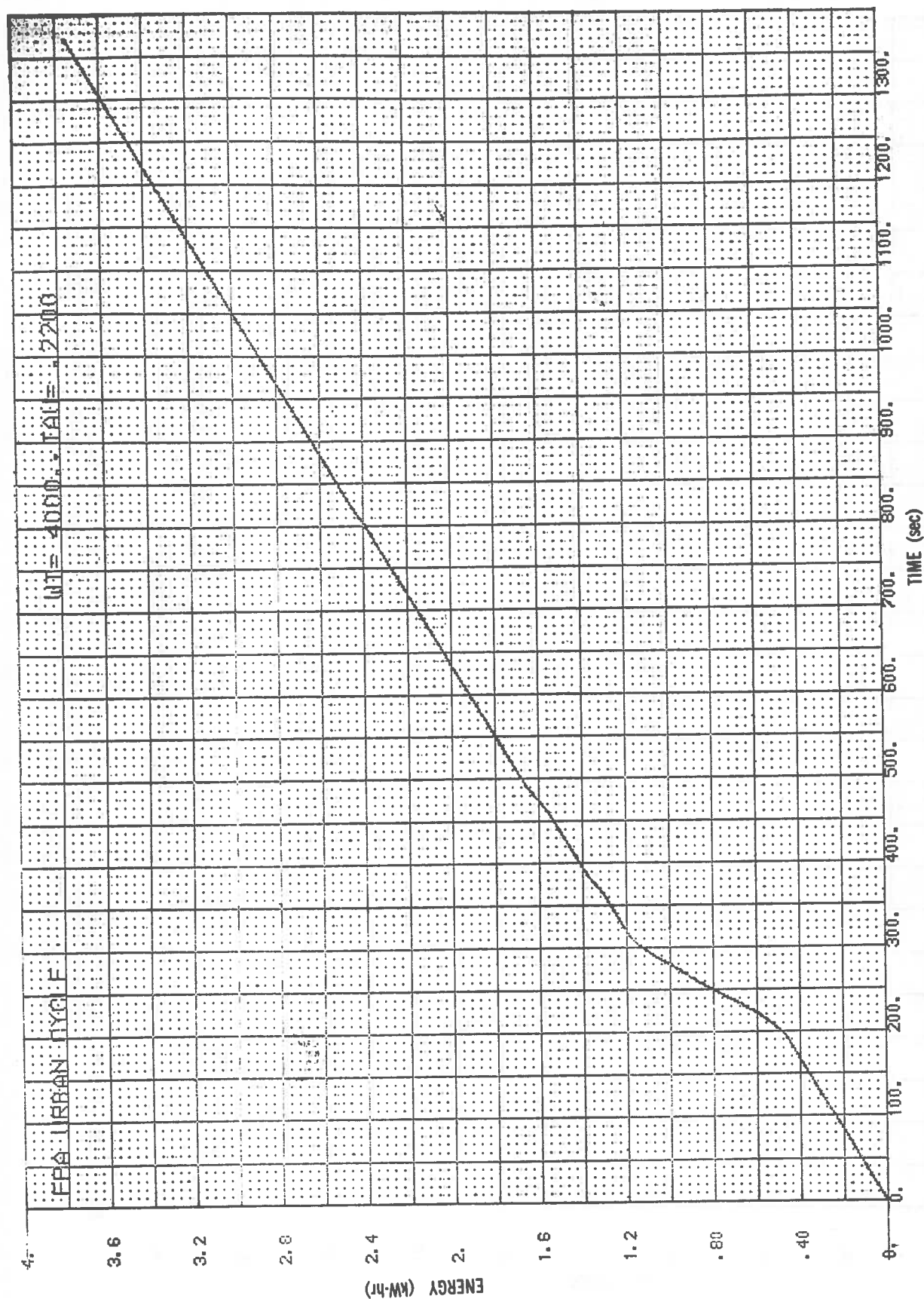


FIGURE 10-87. ENGINE SHAFT ENERGY PROVIDED: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

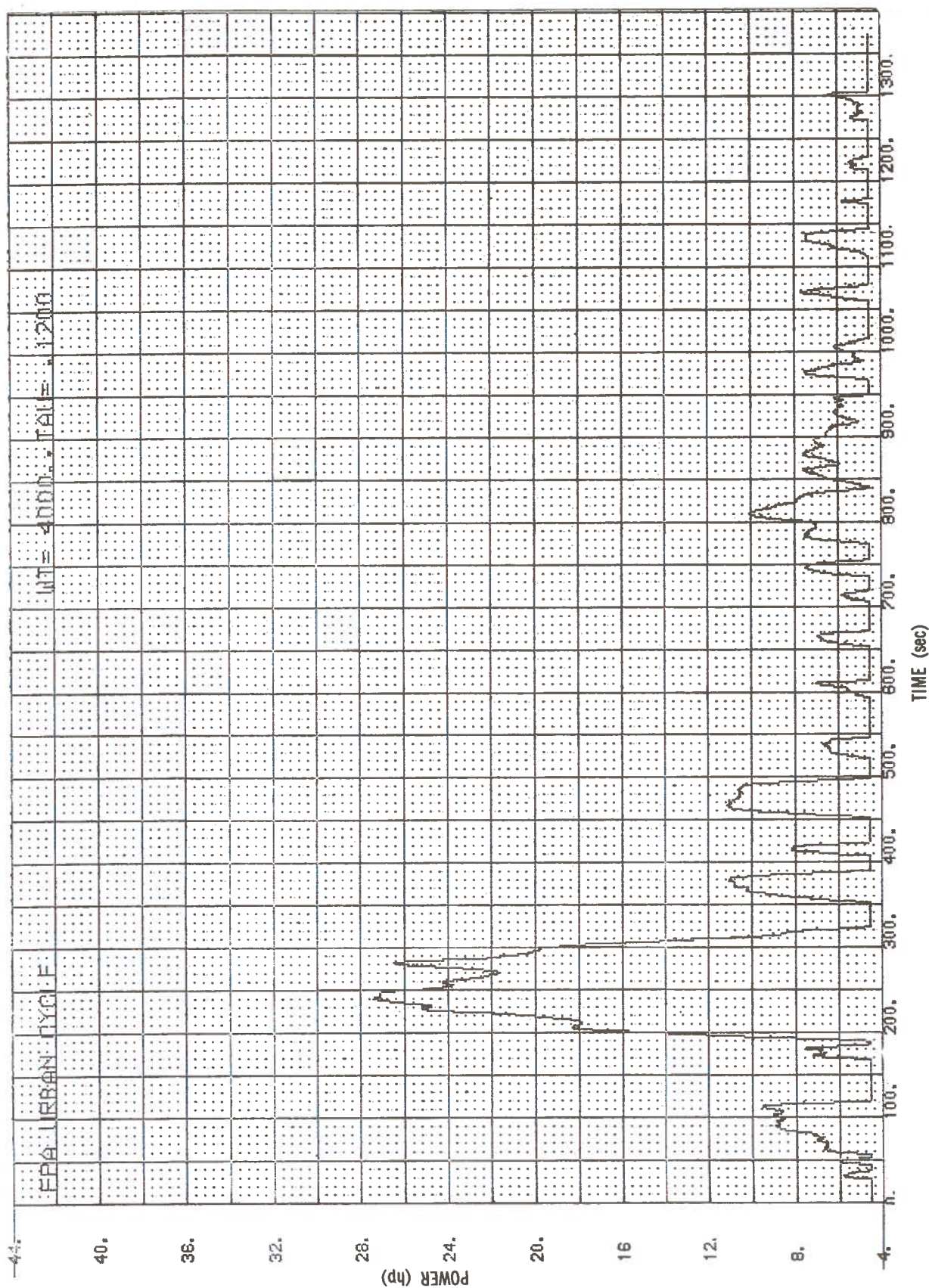


FIGURE 10-88. TRANSMISSION T2 POWER OUTPUT HISTORY (ENGINE-FLYWHEEL LINK):
HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA
URBAN DRIVING CYCLE, $\tau = 0.12$

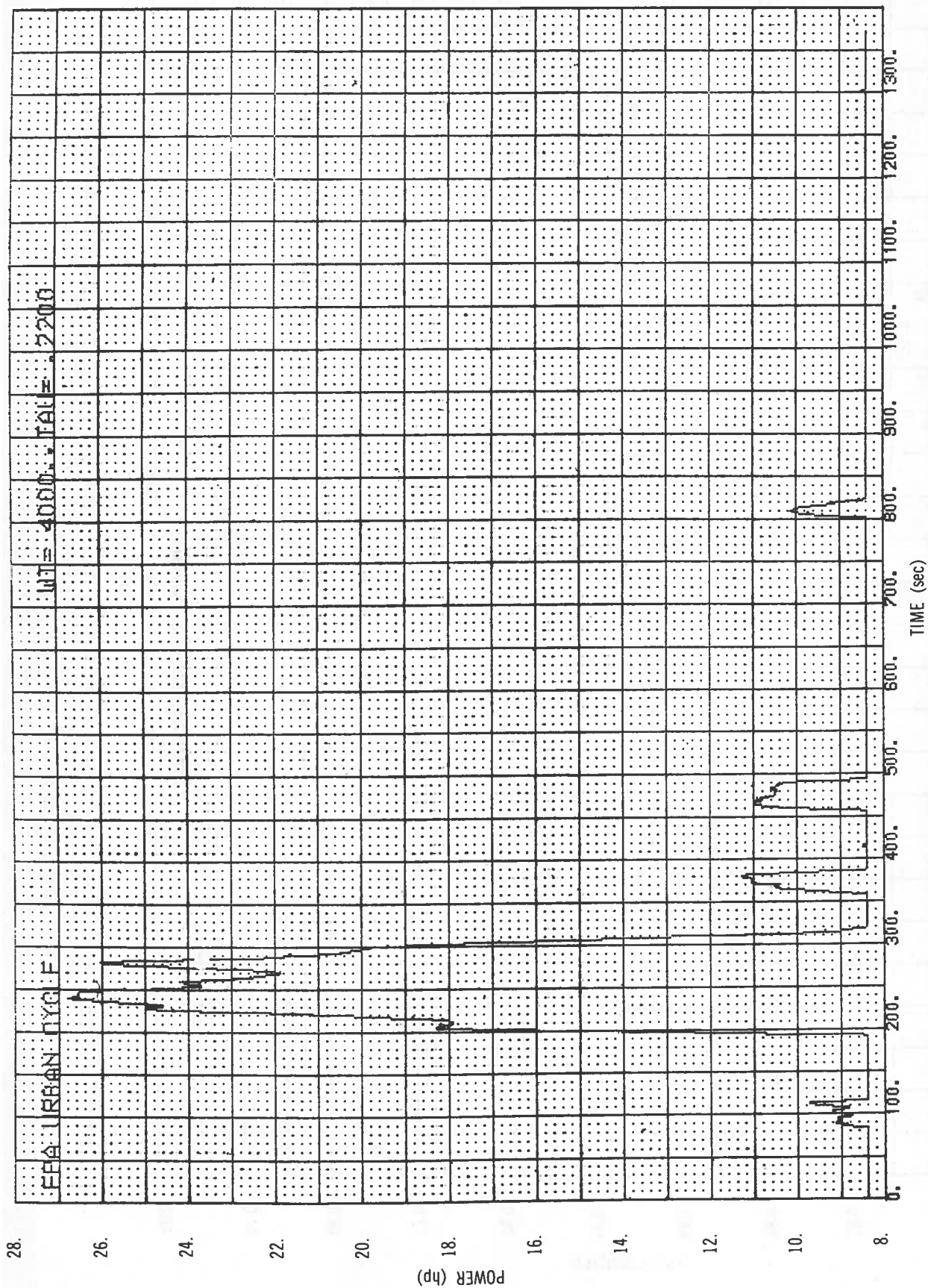


FIGURE 10-89. TRANSMISSION T2 POWER OUTPUT HISTORY (ENGINE-FLYWHEEL LINK):
HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA
URBAN DRIVING CYCLE, $\tau = 0.22$

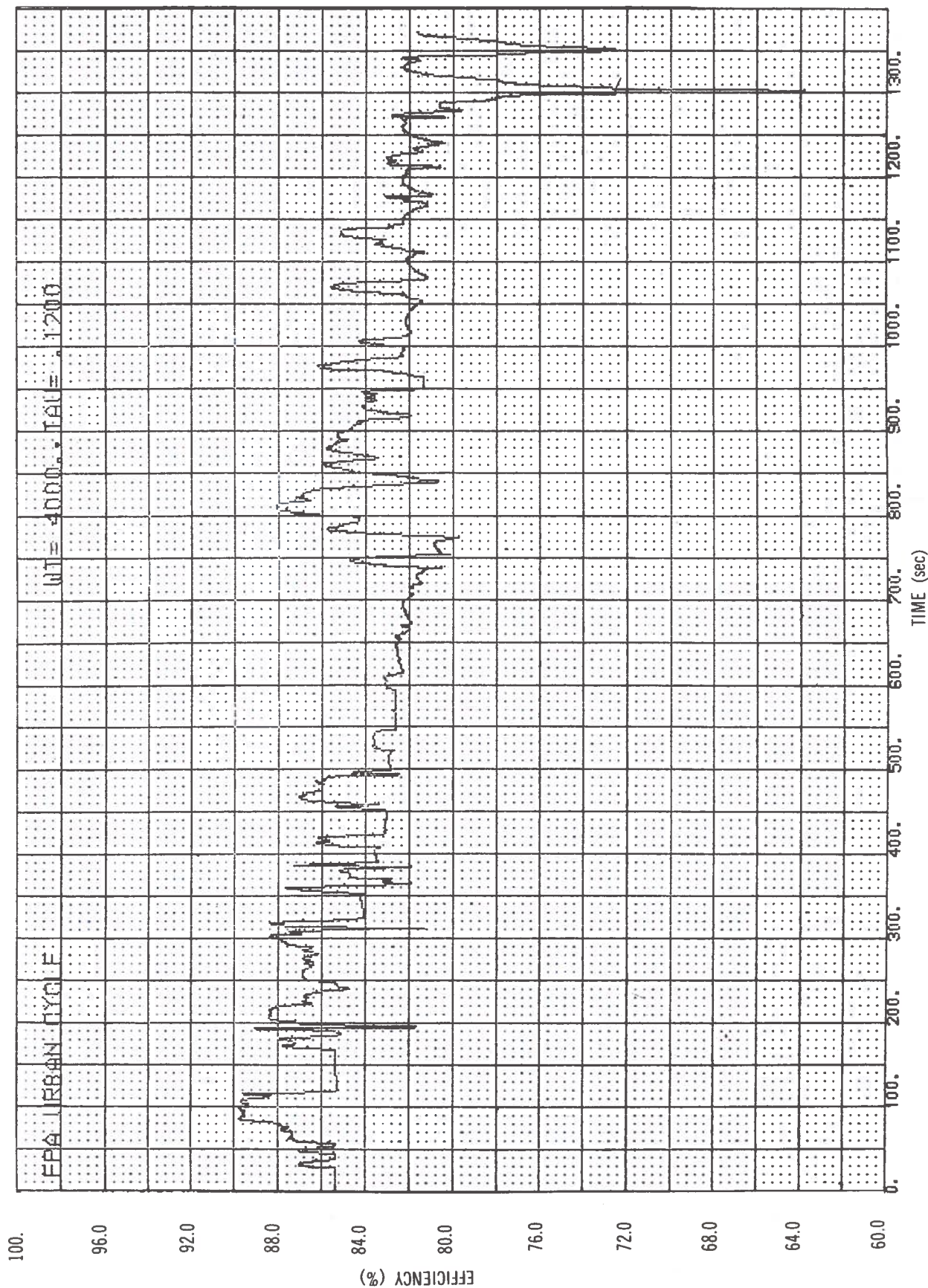


FIGURE 10-90. TRANSMISSION T2 EFFICIENCY HISTORY (ENGINE-FLYWHEEL LINK):
 HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION,
 EPA URBAN DRIVING CYCLE, $\tau = 0.12$

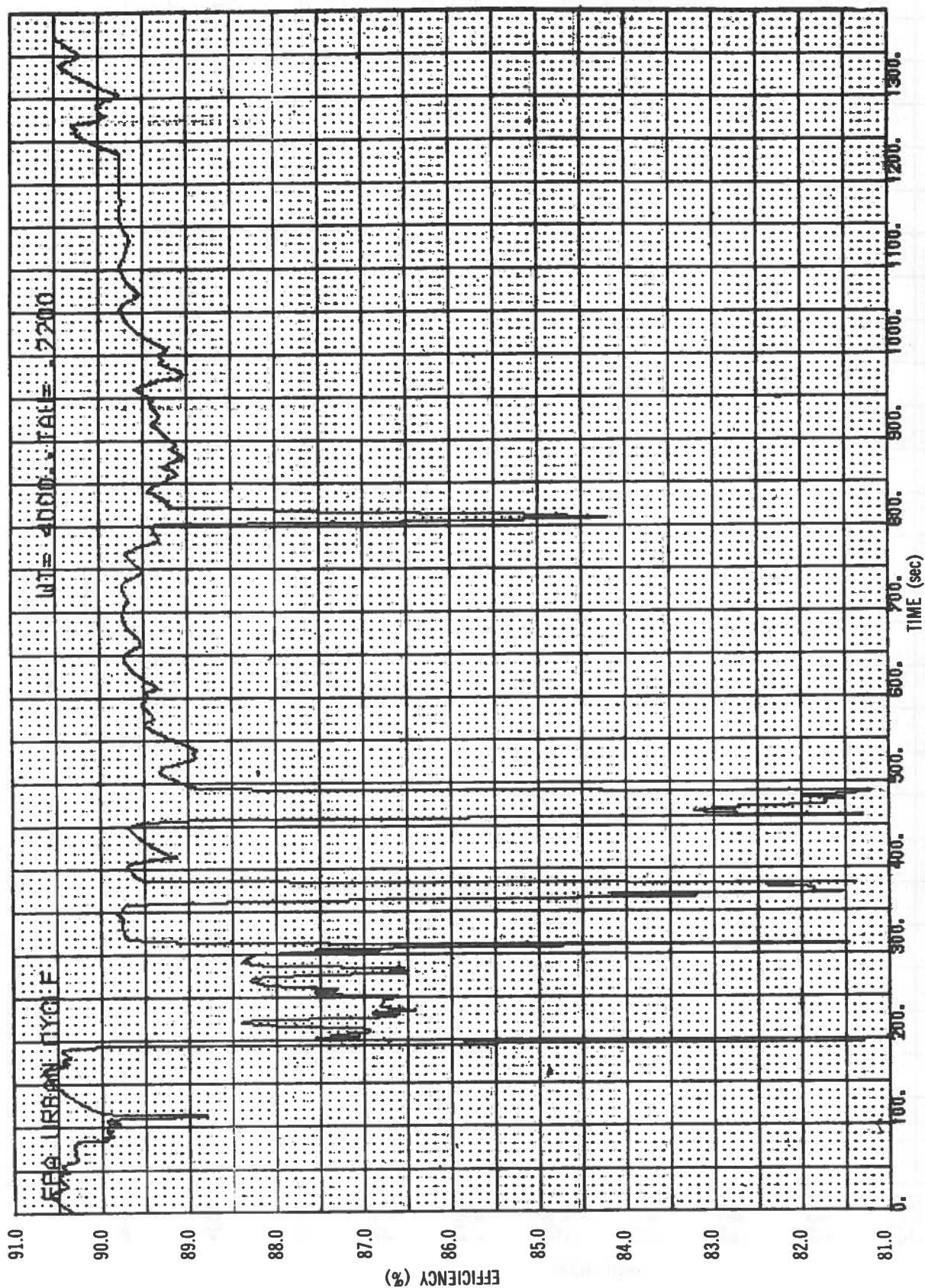


FIGURE 10-91. TRANSMISSION T2 EFFICIENCY HISTORY (ENGINE-FLYWHEEL LINK):
HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION,
EPA URBAN DRIVING CYCLE, $\tau = 0.22$

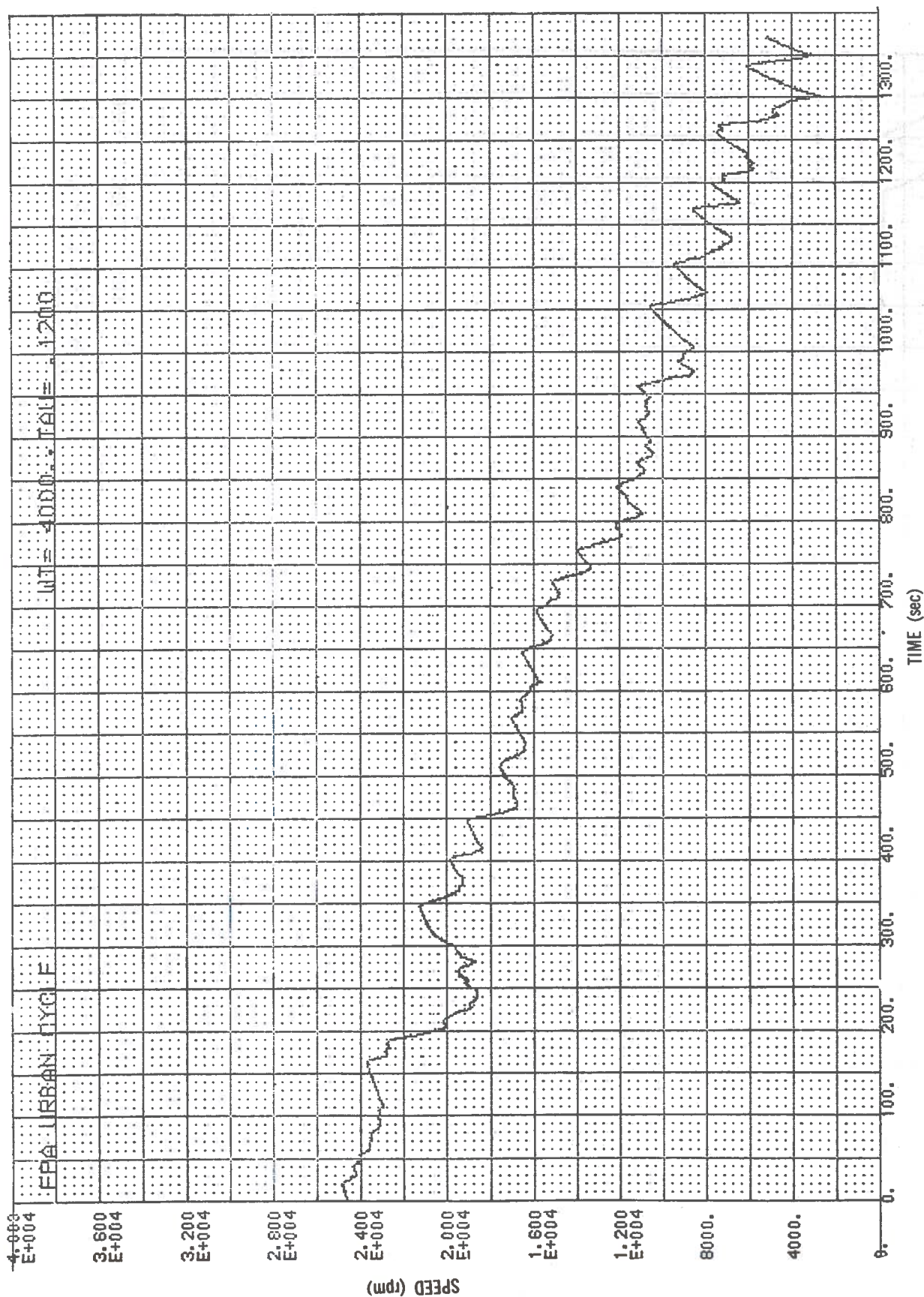


FIGURE 10-92. FLYWHEEL SPEED HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

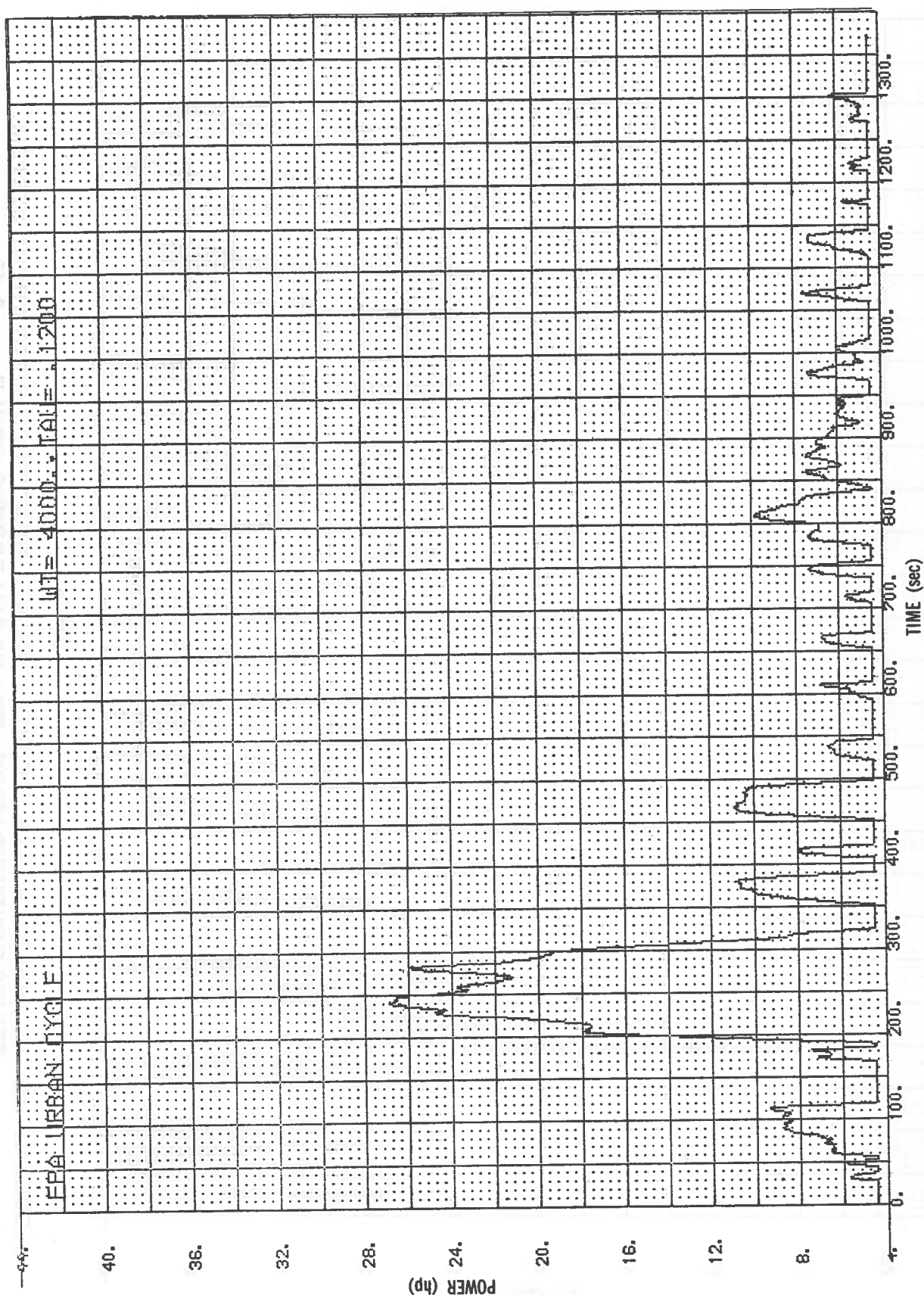


FIGURE 10-93. FLYWHEEL POWER INPUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

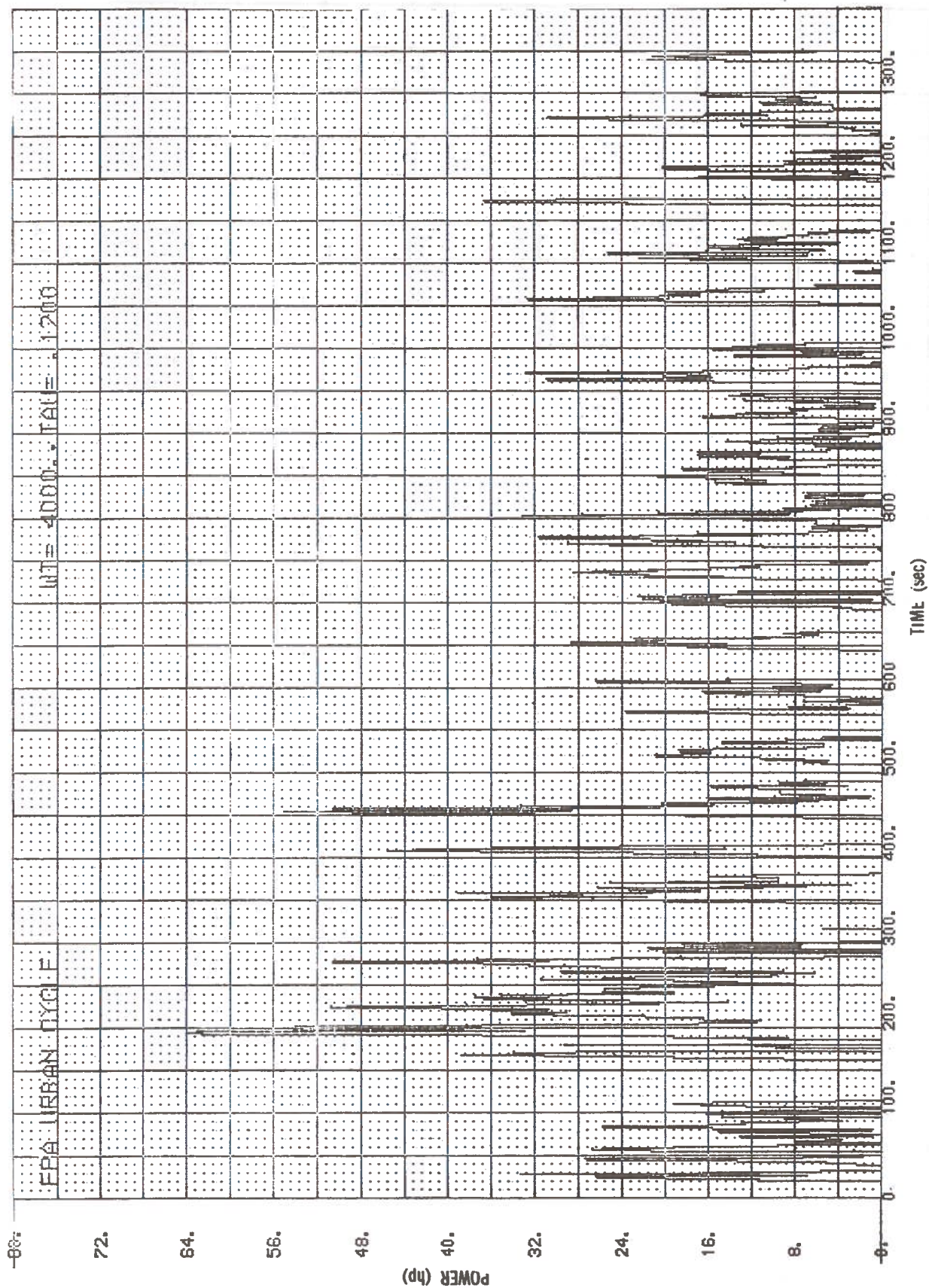


FIGURE 10-94. FLYWHEEL POWER OUTPUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

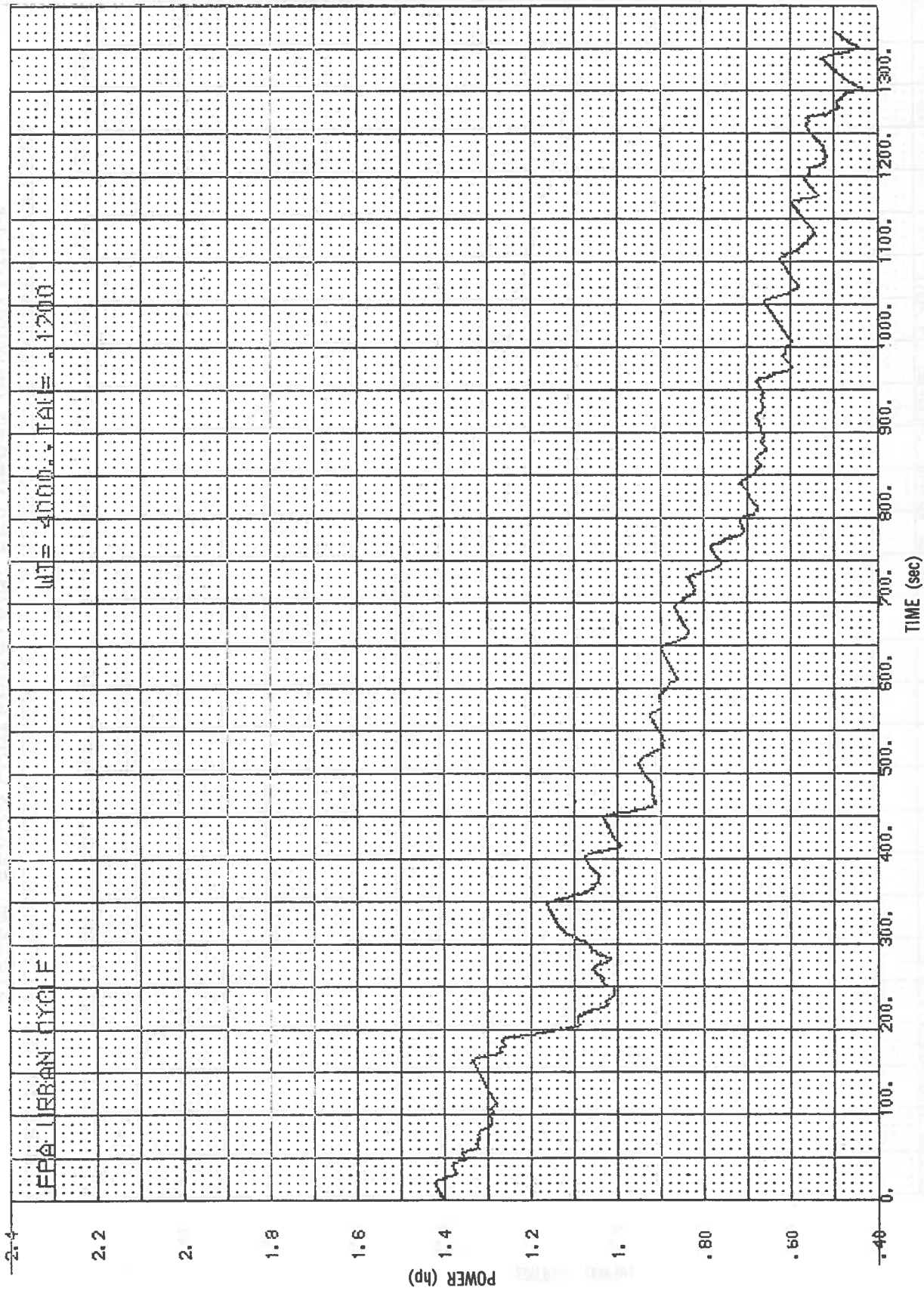


FIGURE 10-95. FLYWHEEL PARASITIC POWER LOSS HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

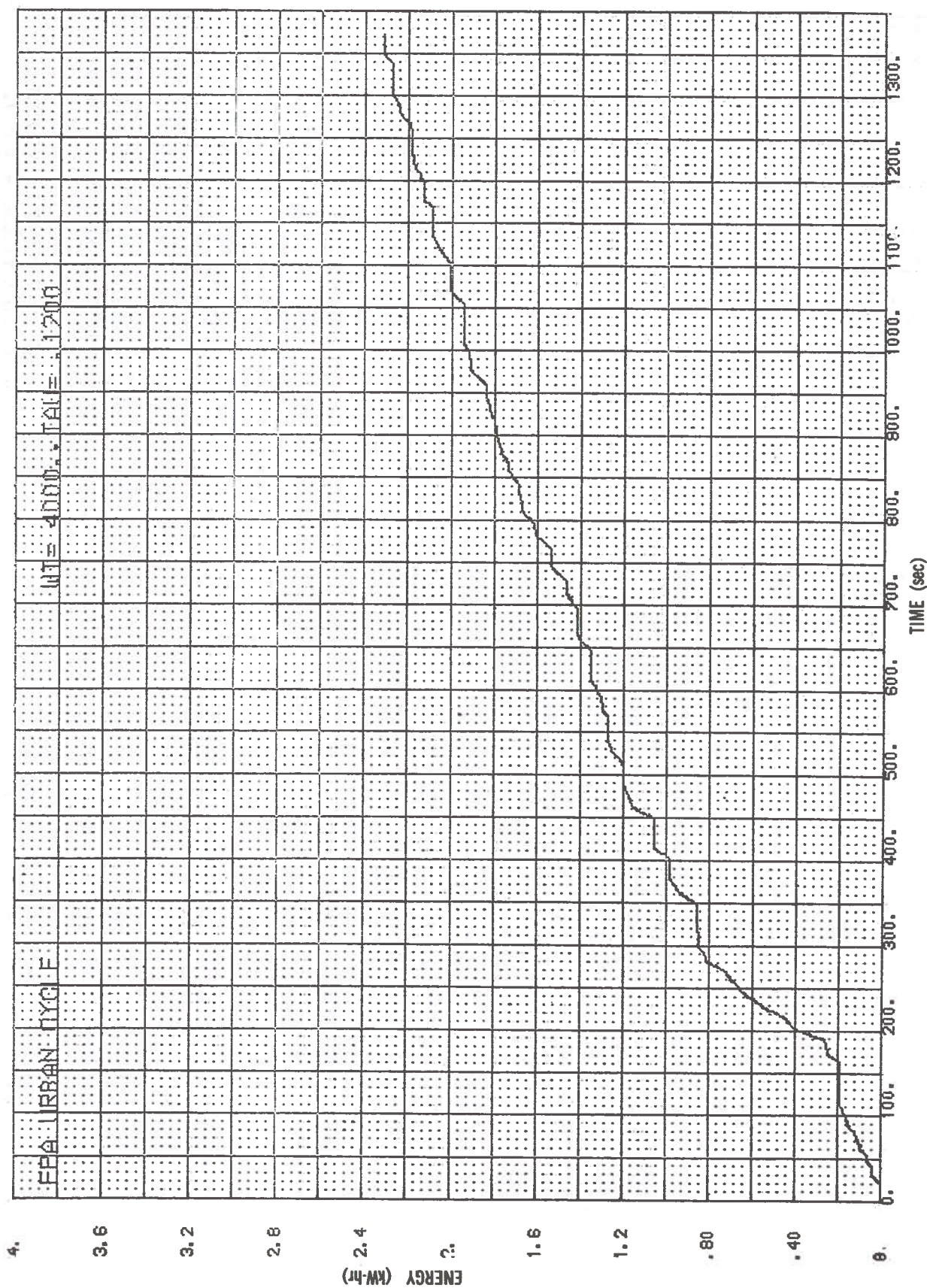


FIGURE 10-96. FLYWHEEL TOTAL ENERGY OUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

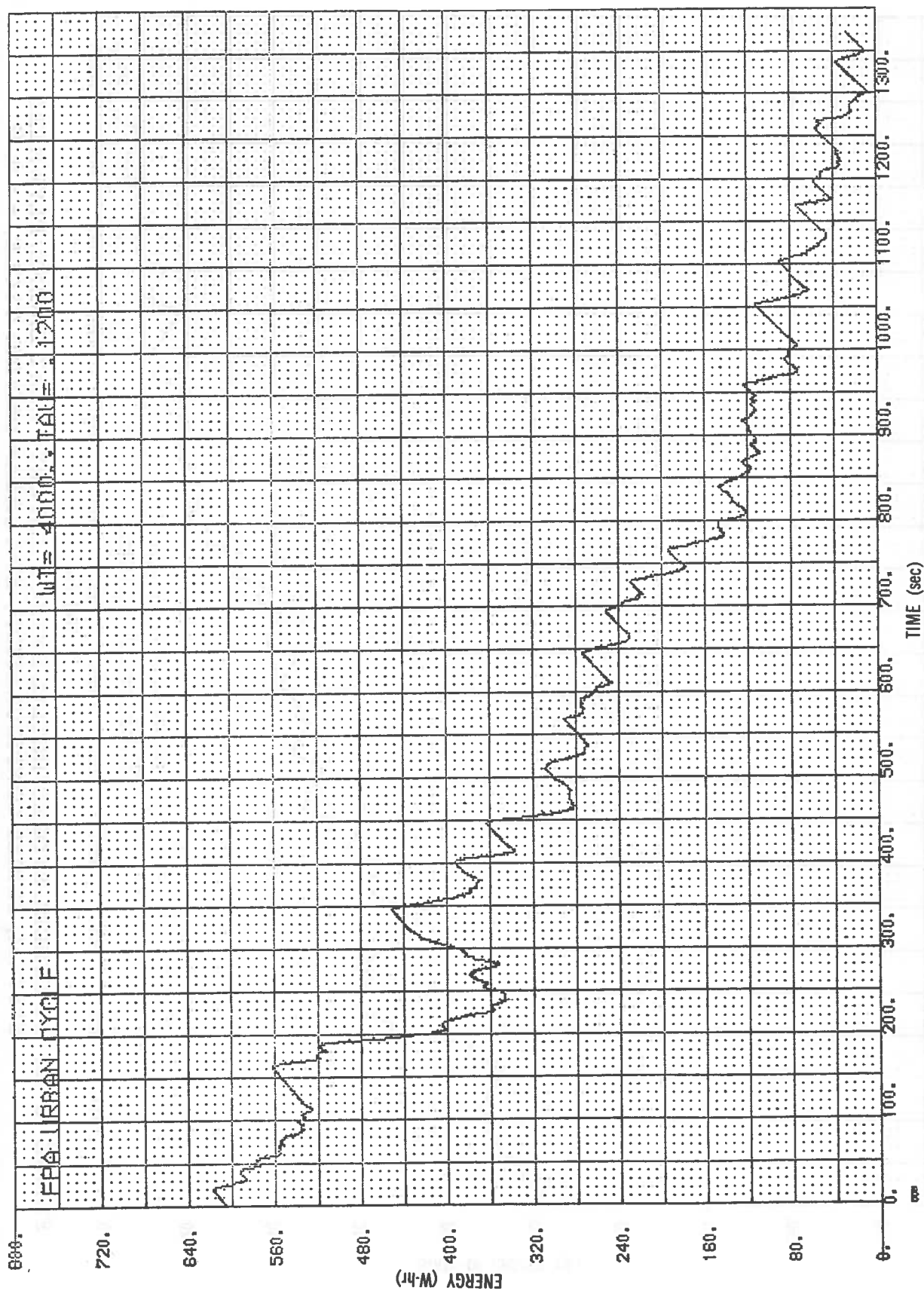


FIGURE 10-97. FLYWHEEL STORED ENERGY HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

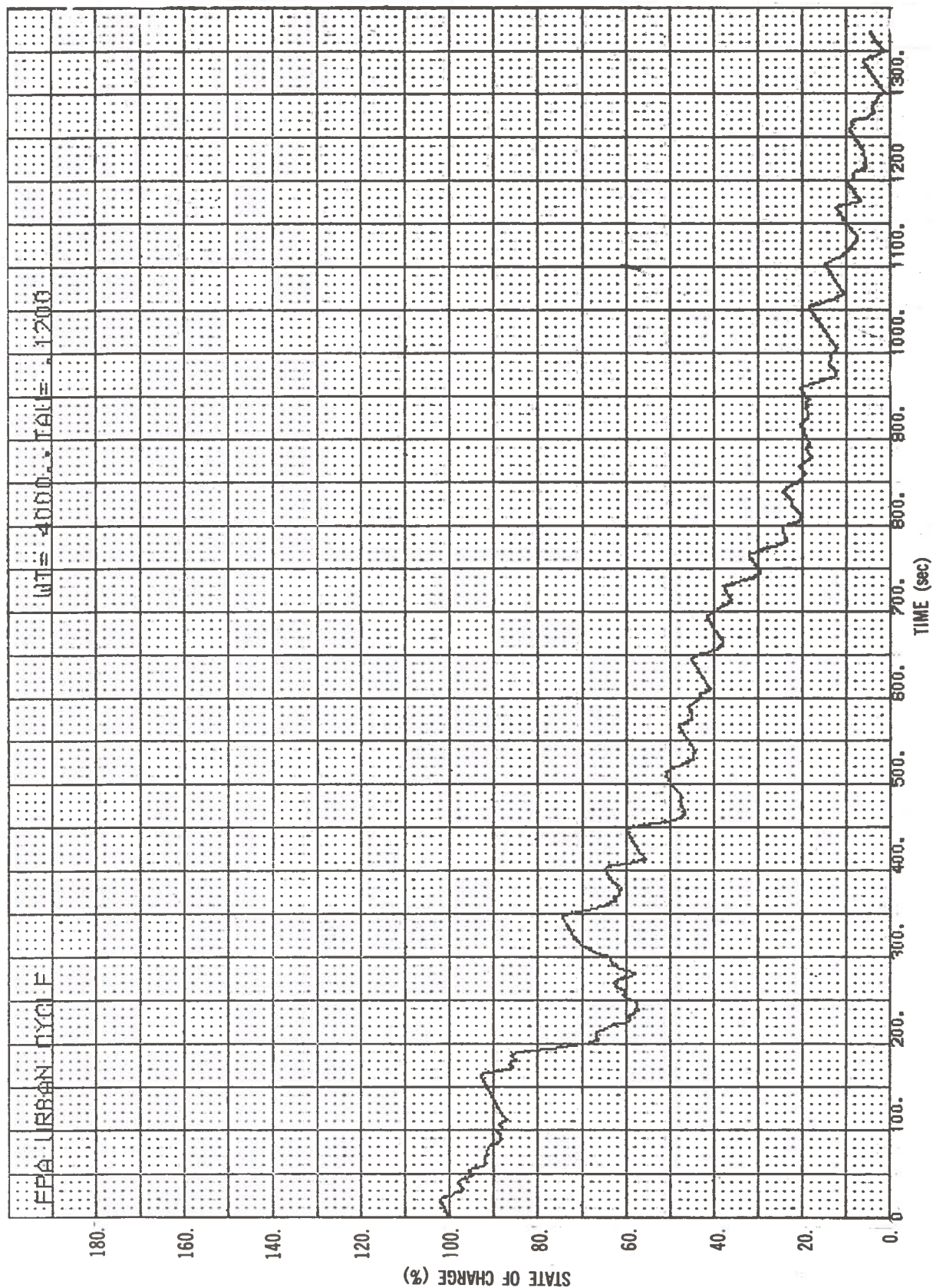


FIGURE 10-98. FLYWHEEL STORED/INITIAL ENERGY HISTORY; HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

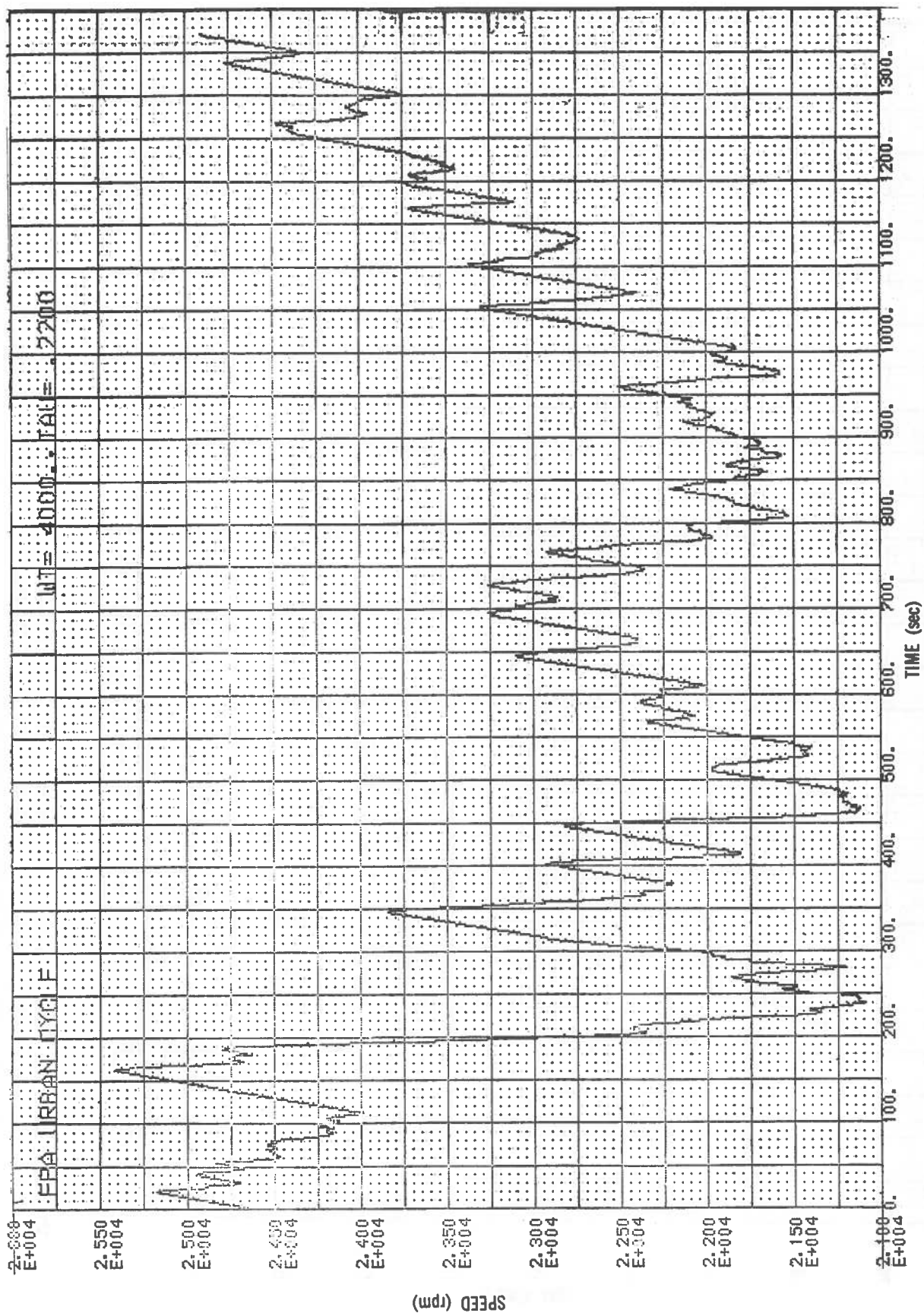


FIGURE 10-99. FLYWHEEL SPEED HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

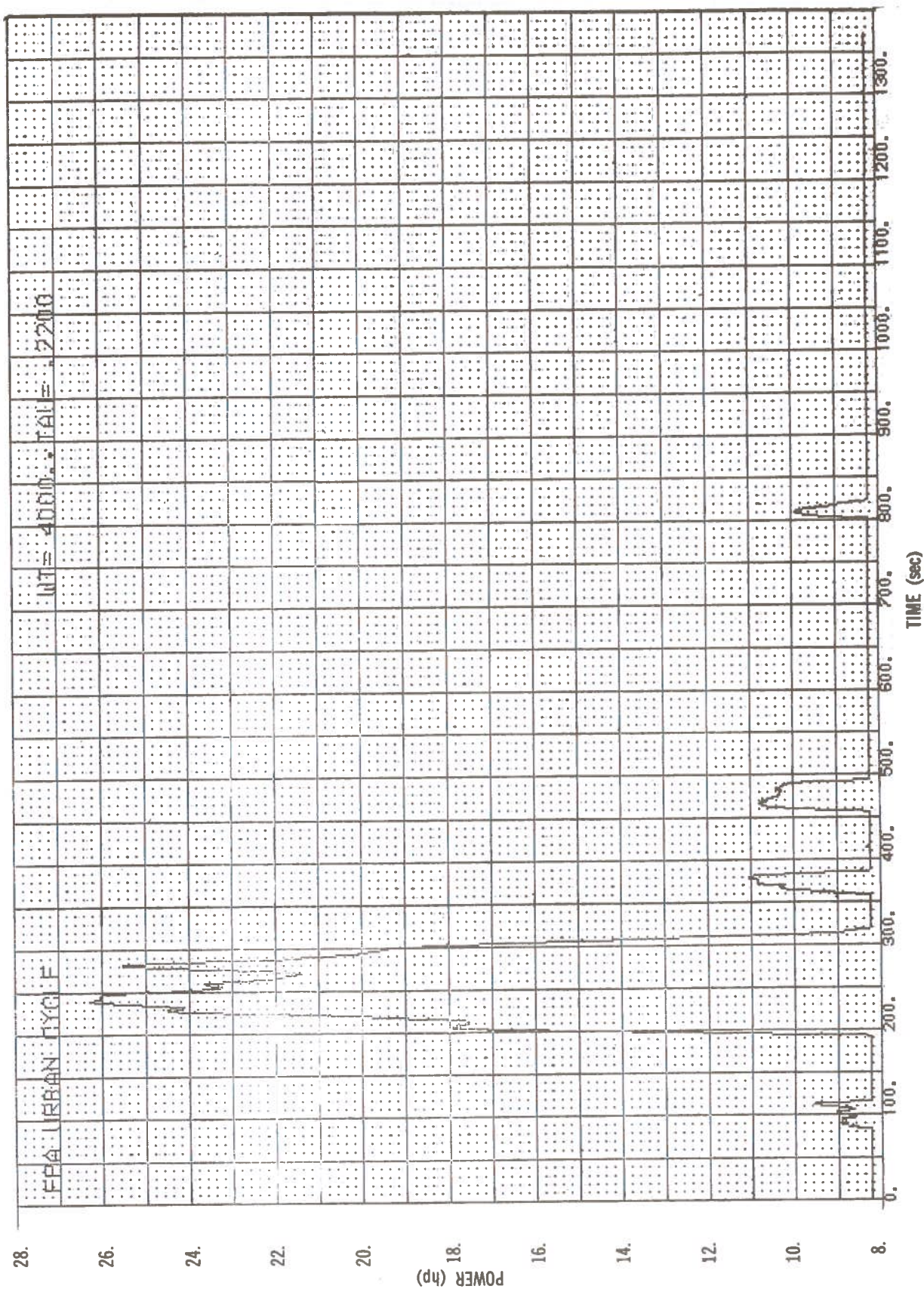


FIGURE 10-100. FLYWHEEL POWER INPUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM.
SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

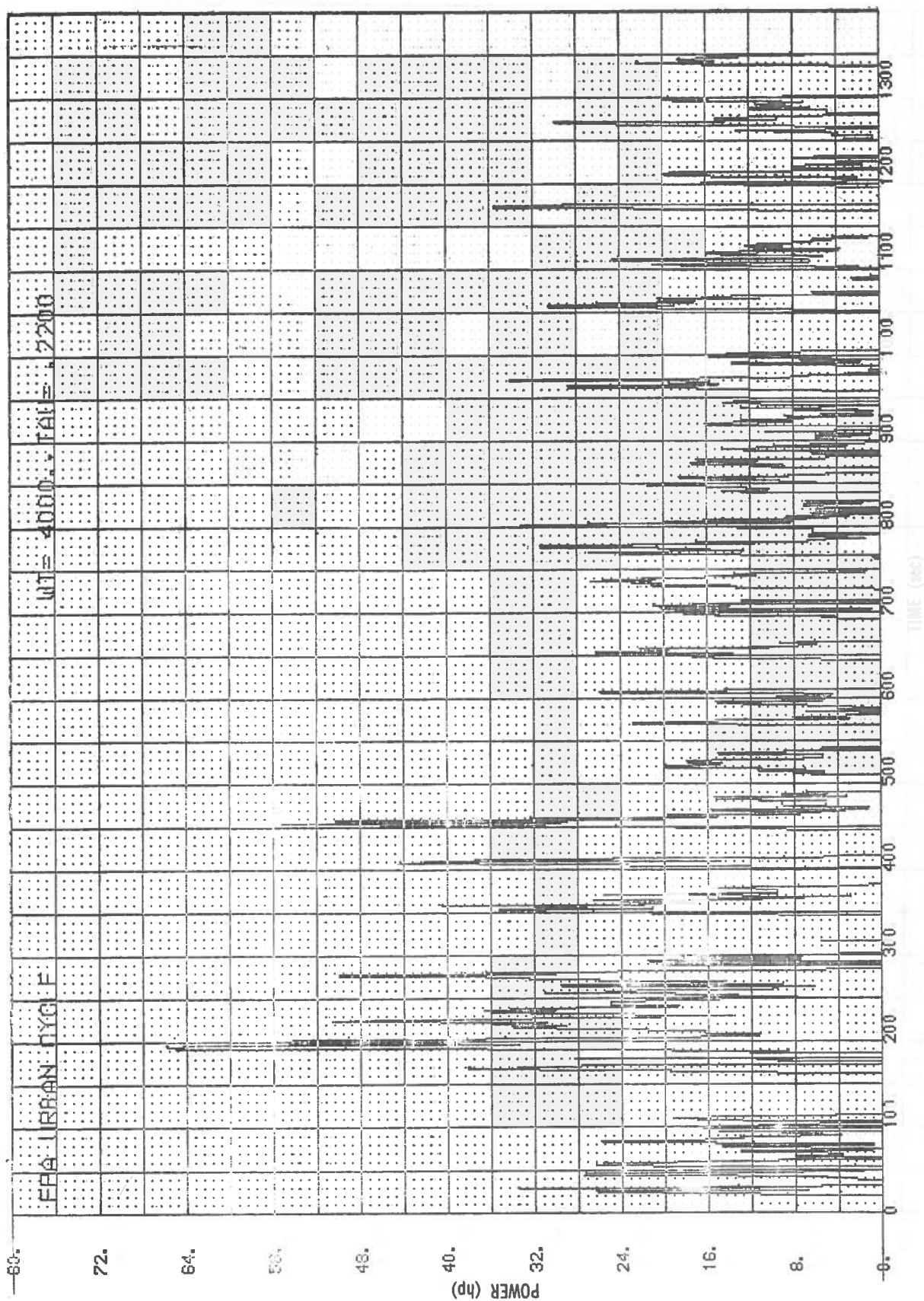


FIGURE 10-101: FLYWHEEL POWER OUTPUT HISTORY; HEAT-ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION; EPA URBAN DRIVING CYCLE; $\tau = 0.22$

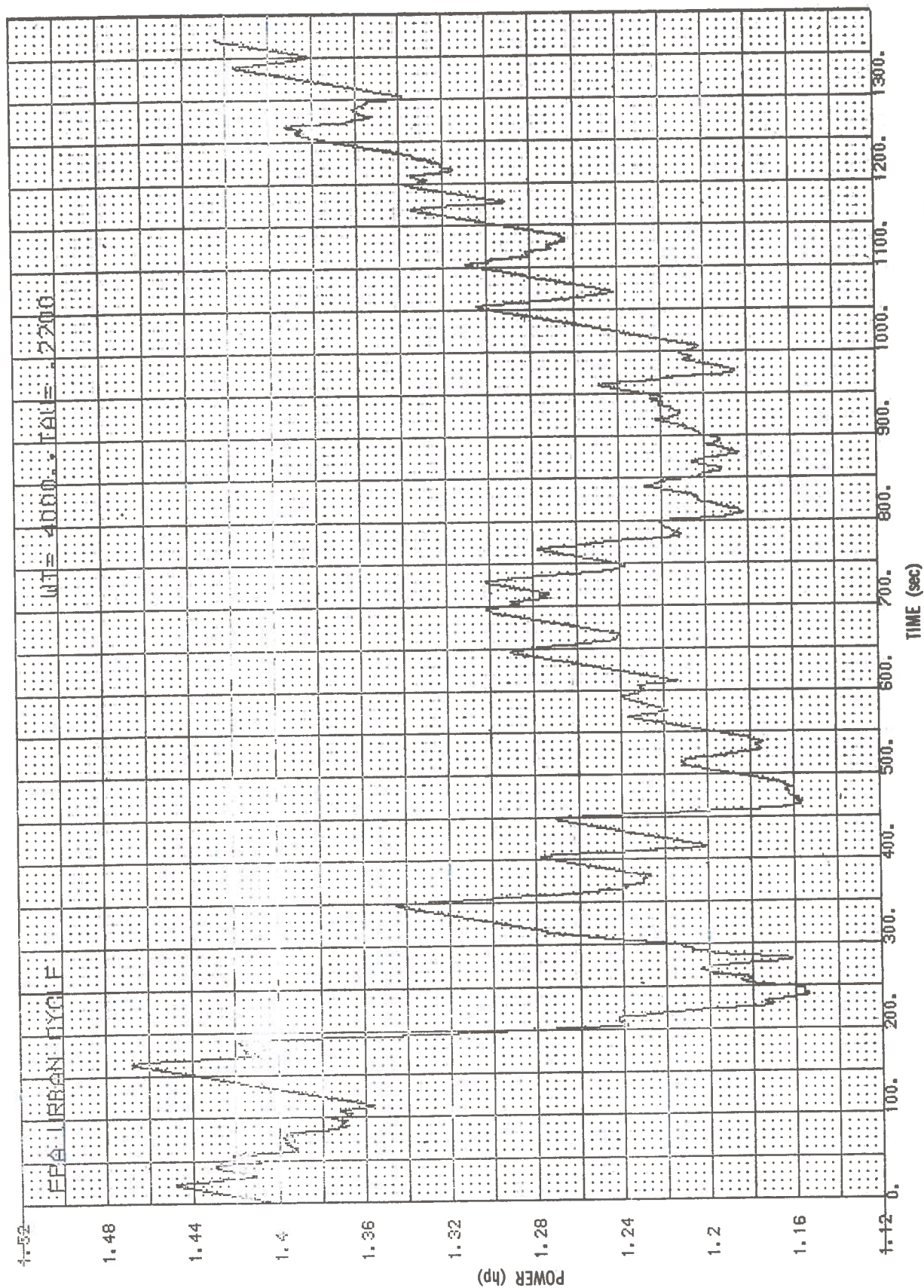


FIGURE 10-102. FLYWHEEL PARASITIC POWER LOSS HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

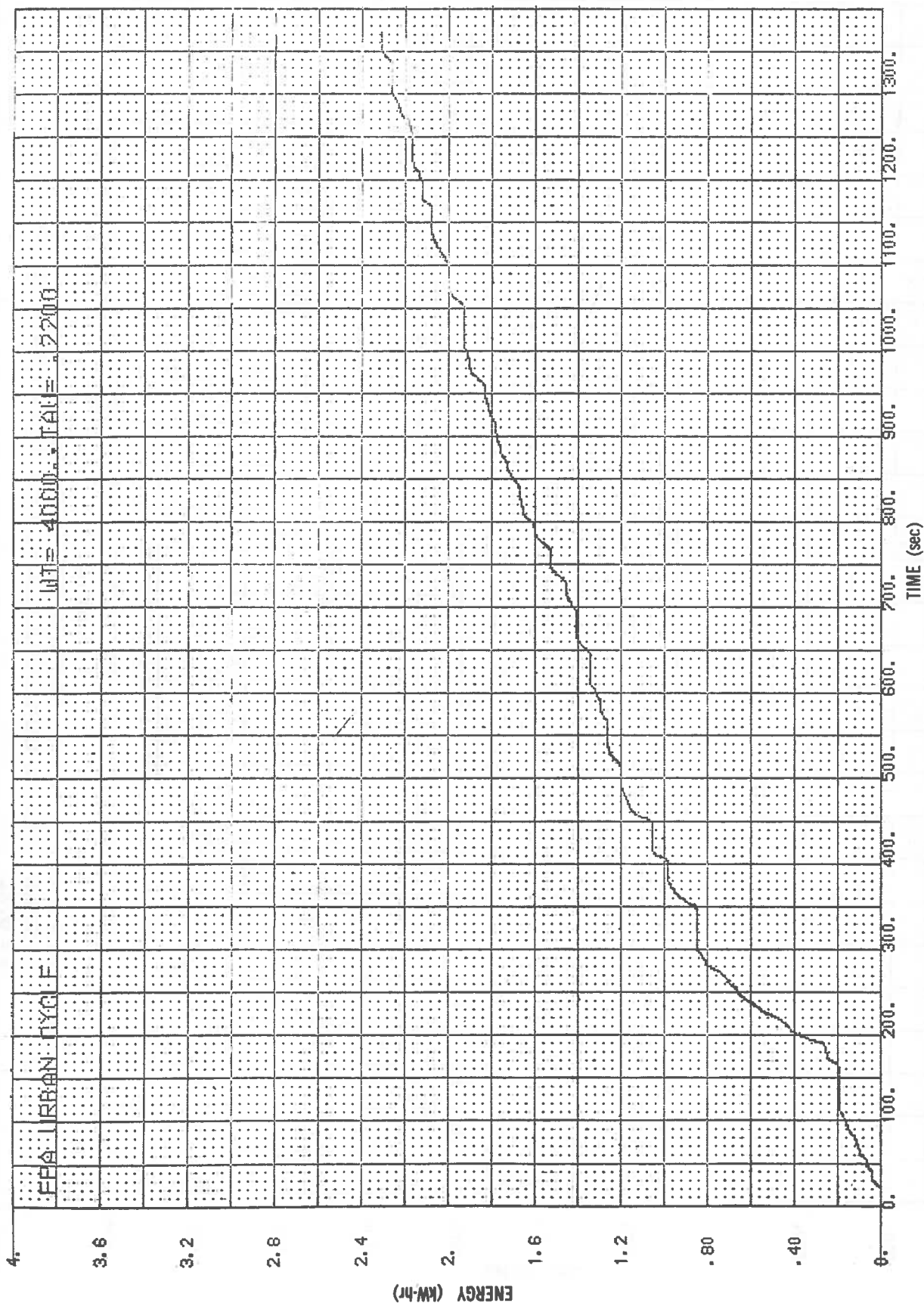


FIGURE 10-103. FLYWHEEL TOTAL ENERGY OUT HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

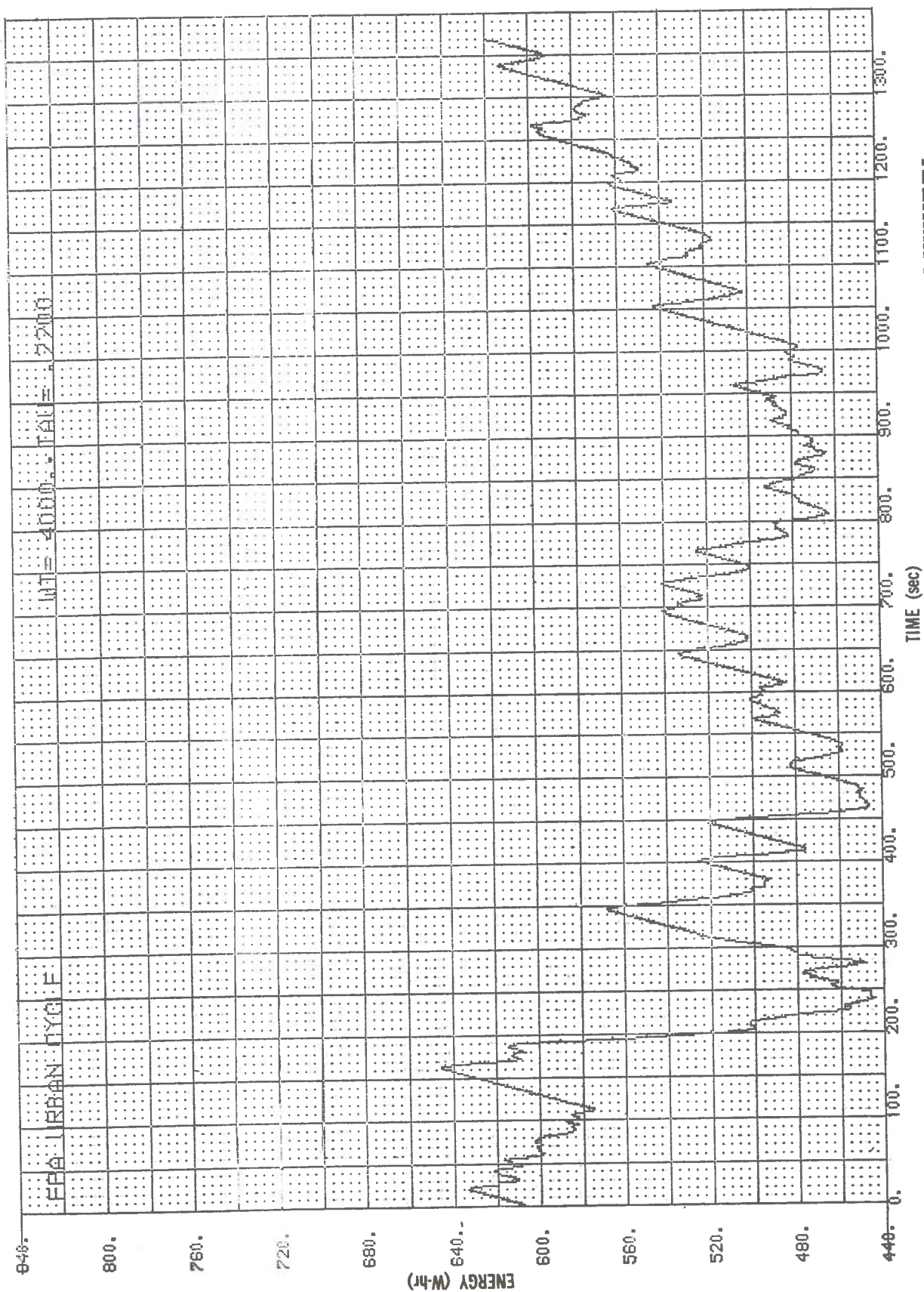


FIGURE 10-104. FLYWHEEL STORED ENERGY HISTORY: HEAT ENGINE FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

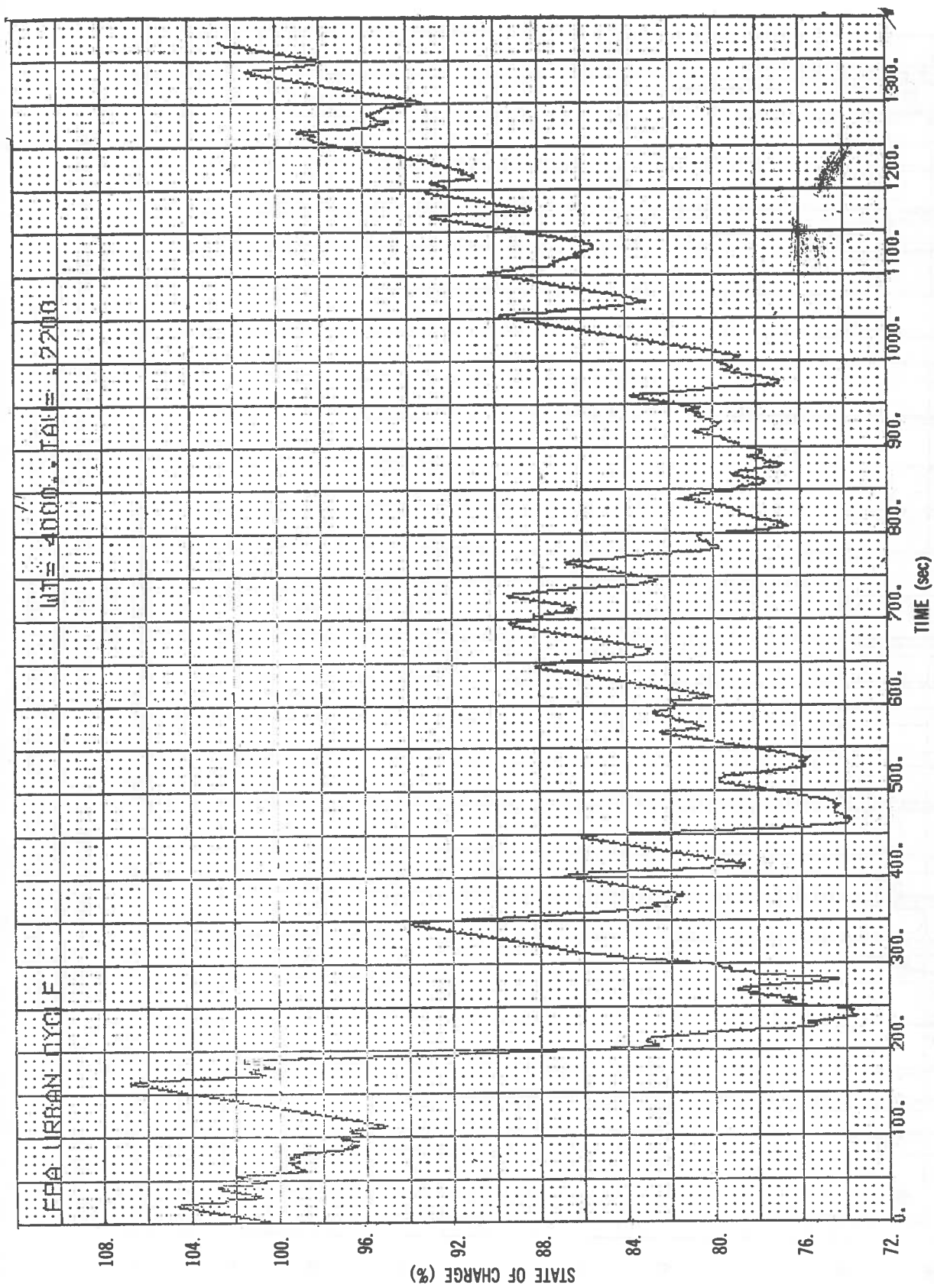


FIGURE 10-105. FLYWHEEL STORED/INITIAL ENERGY HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

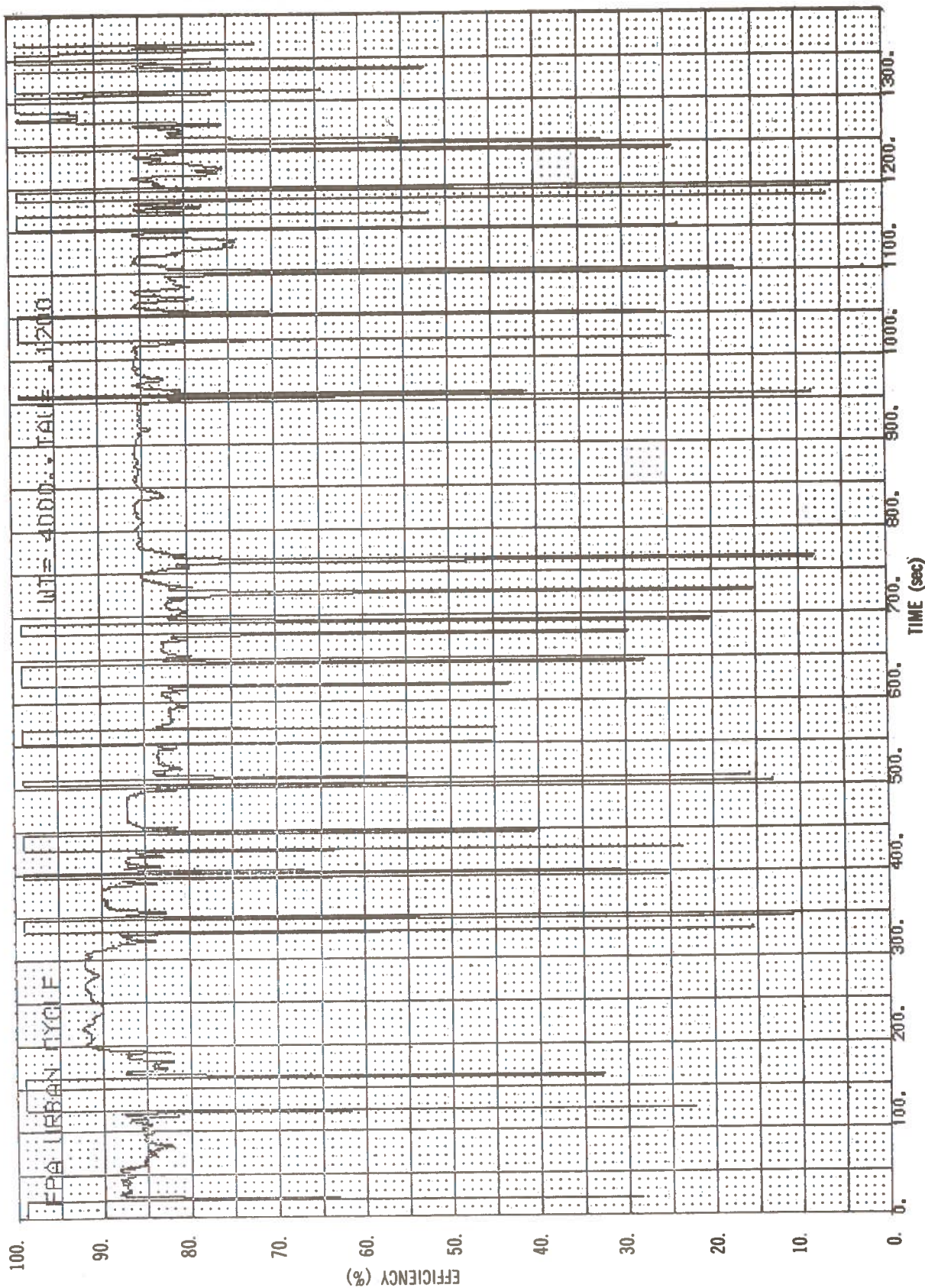


FIGURE 10-106. TRANSMISSION T3 EFFICIENCY HISTORY (FLYWHEEL-VEHICLE DRIVE WHEELS LINK): HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.12$

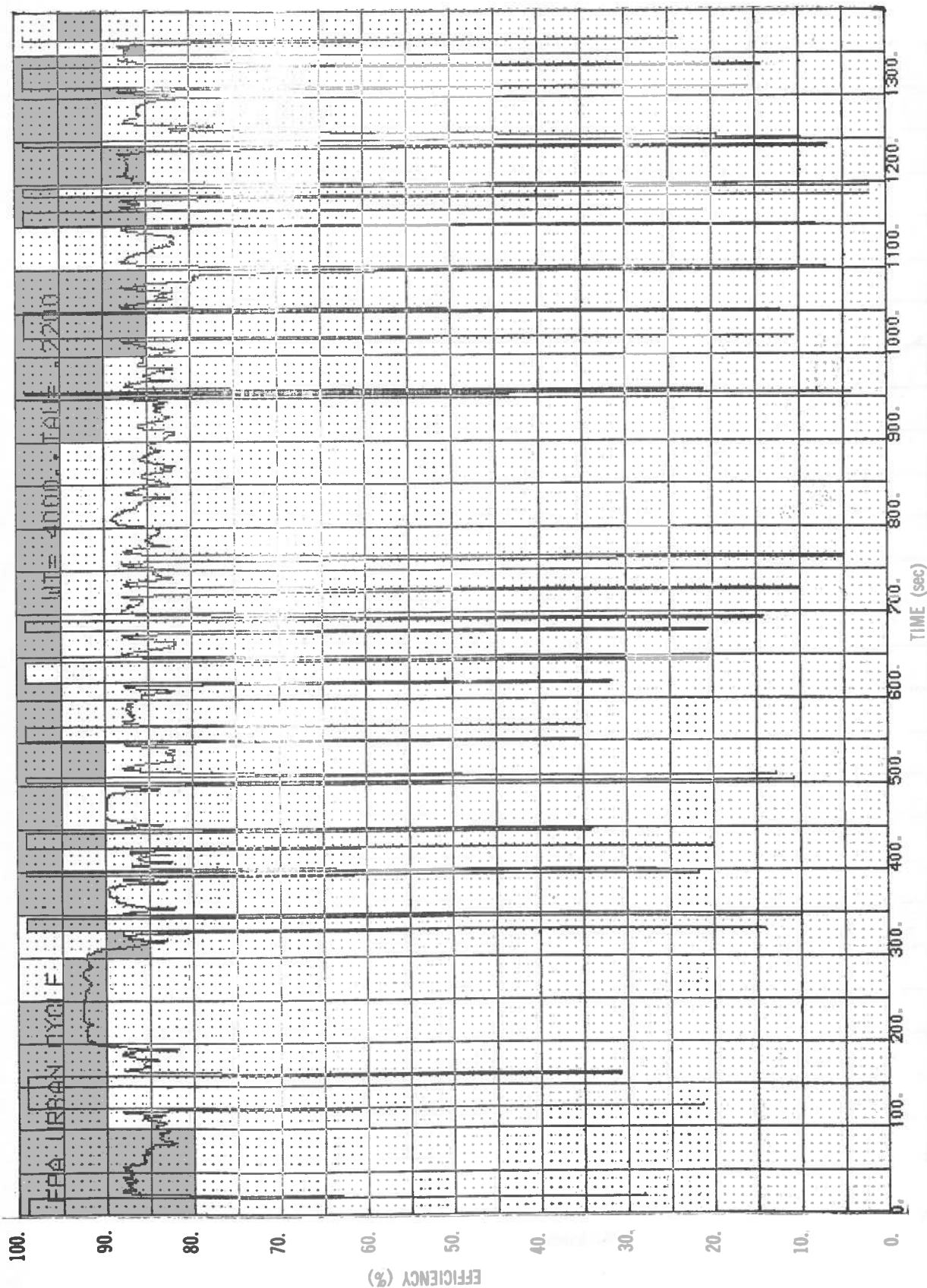


FIGURE 10-107. TRANSMISSION T3 EFFICIENCY HISTORY (FLYWHEEL-VEHICLE DRIVE WHEELS LINK): HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE, $\tau = 0.22$

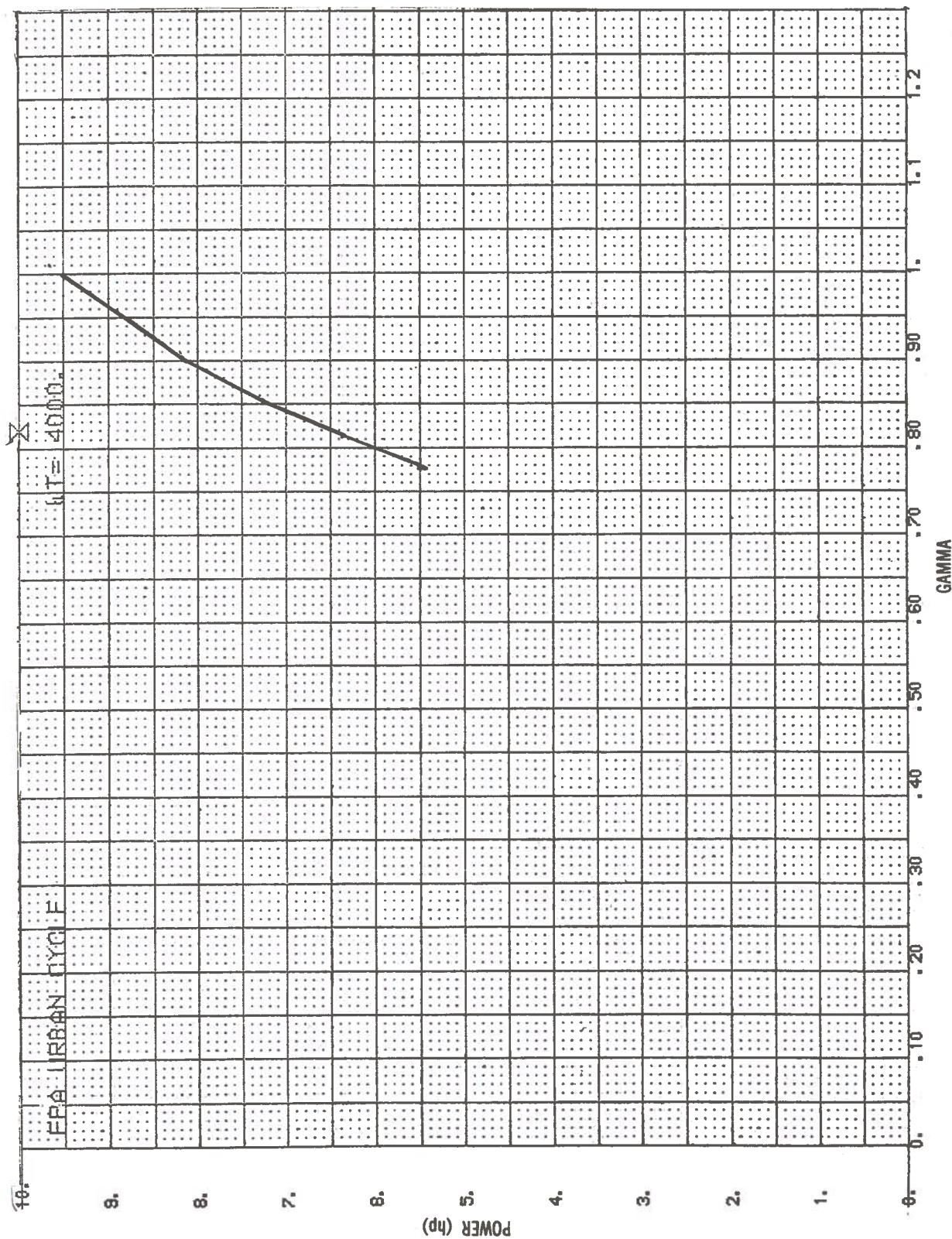


FIGURE 10-108. ENGINE POWER USED FOR PROPULSION: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

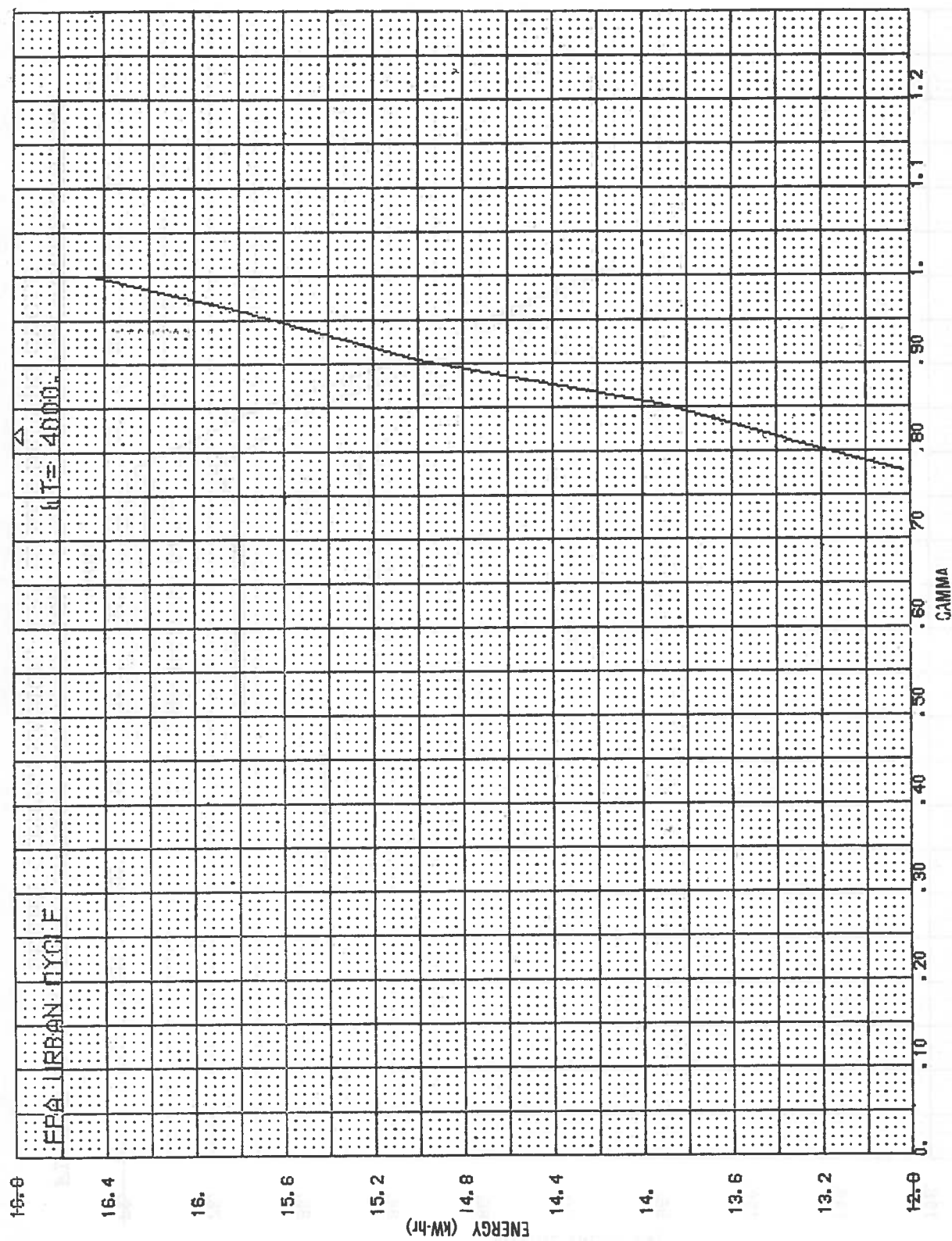


FIGURE 10-109. ENGINE FUEL ENERGY PROVIDED: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE

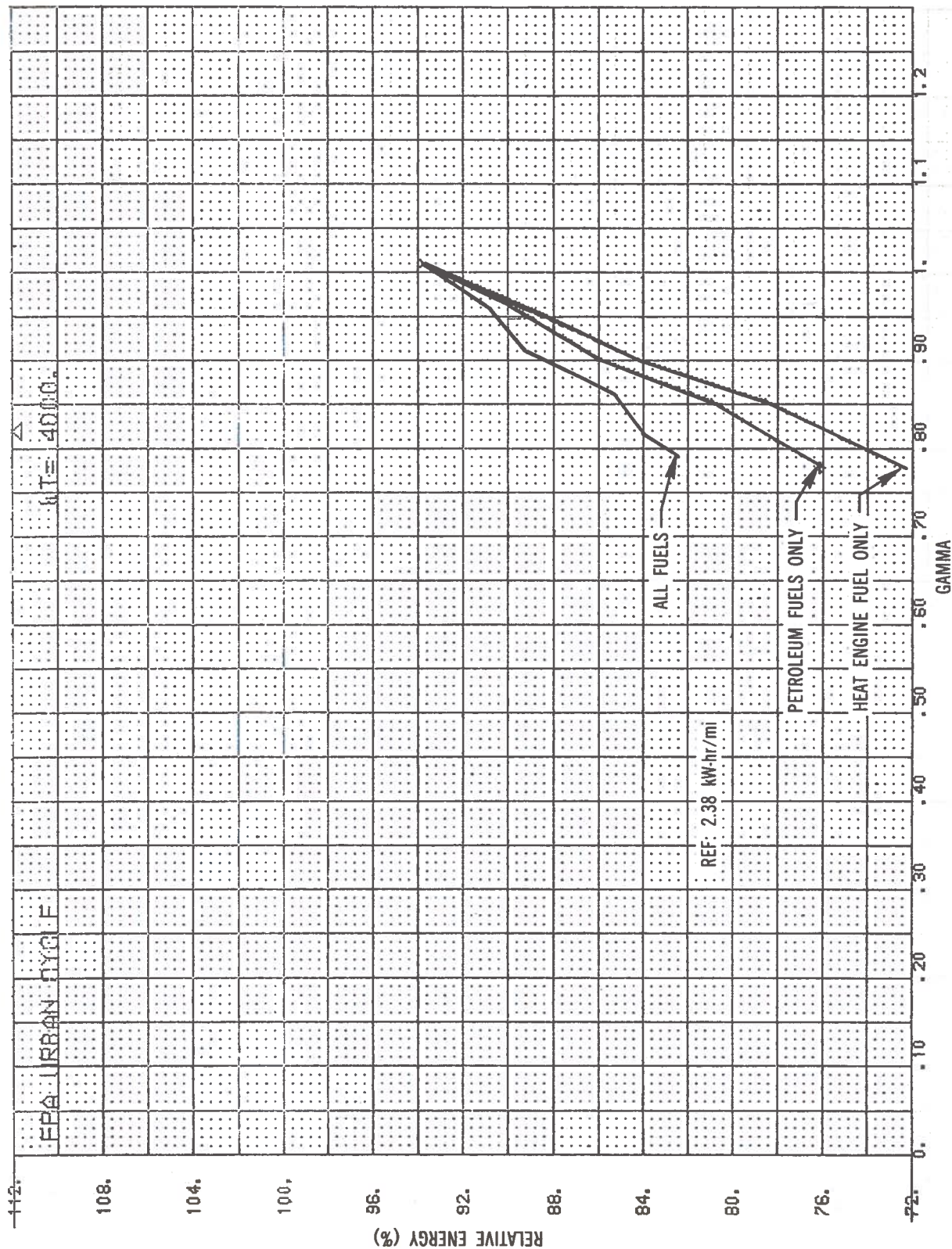
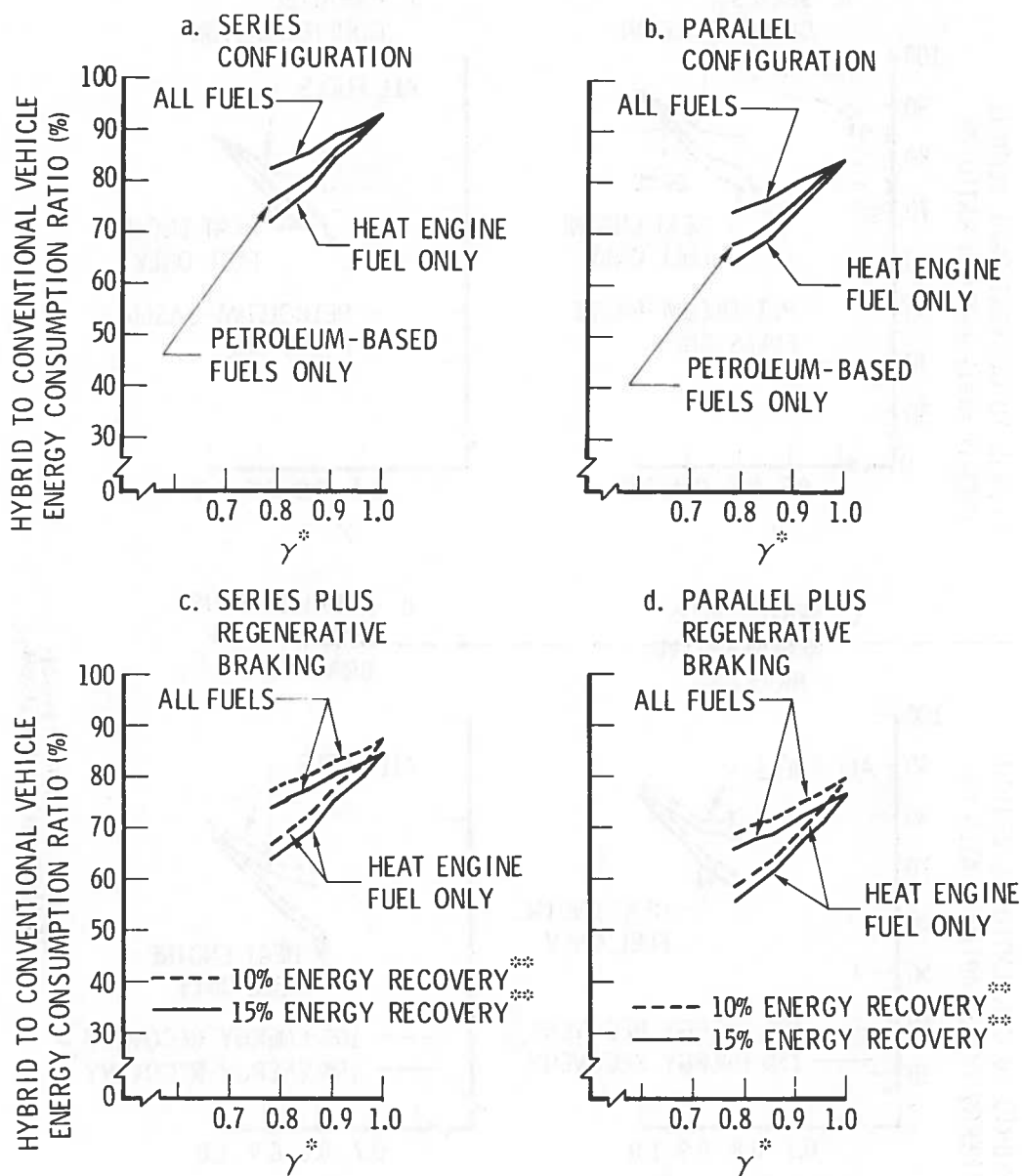


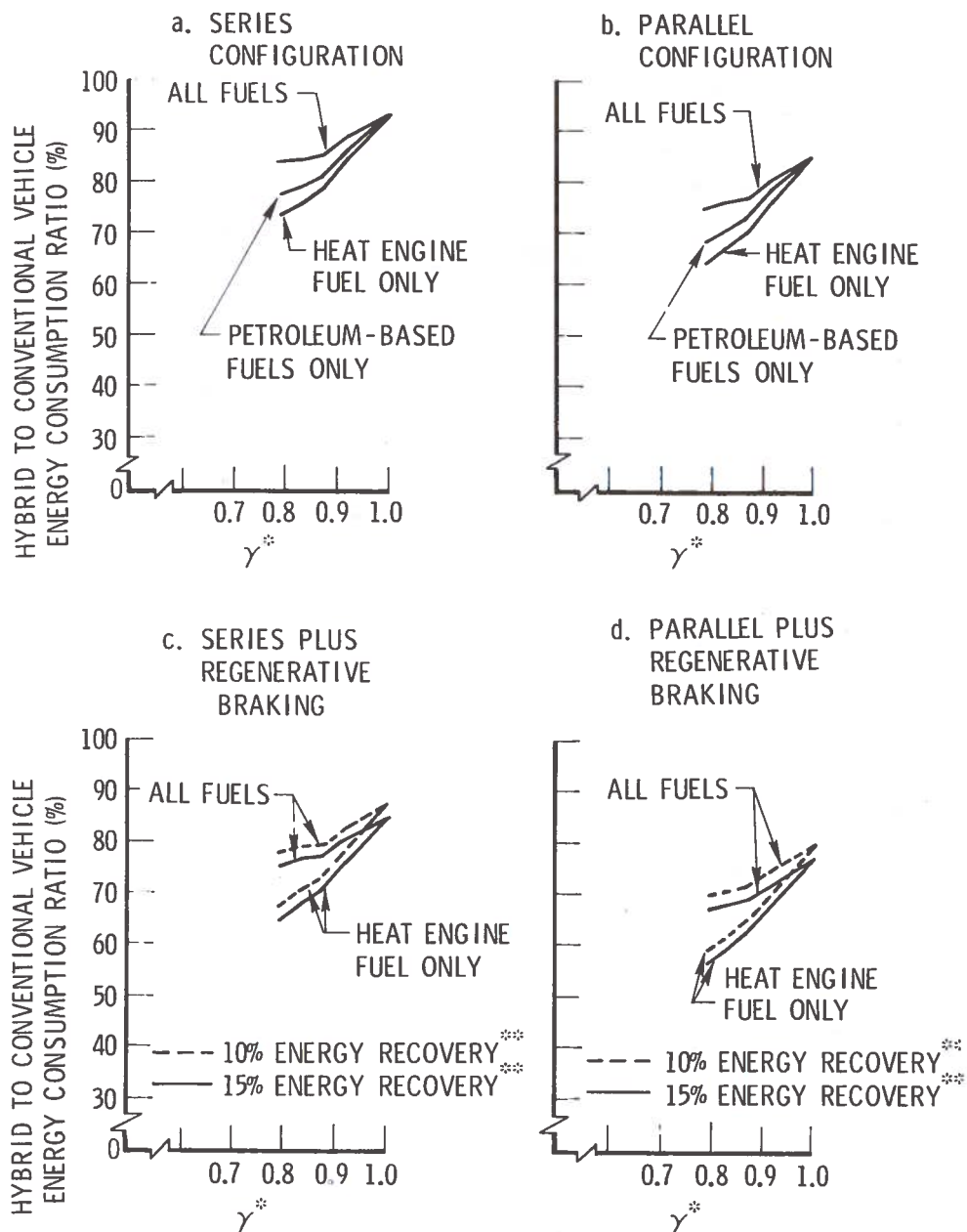
FIGURE 10-110. FUEL ENERGY CONSUMPTION: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA URBAN DRIVING CYCLE



* 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 10-111. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 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 10-112. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

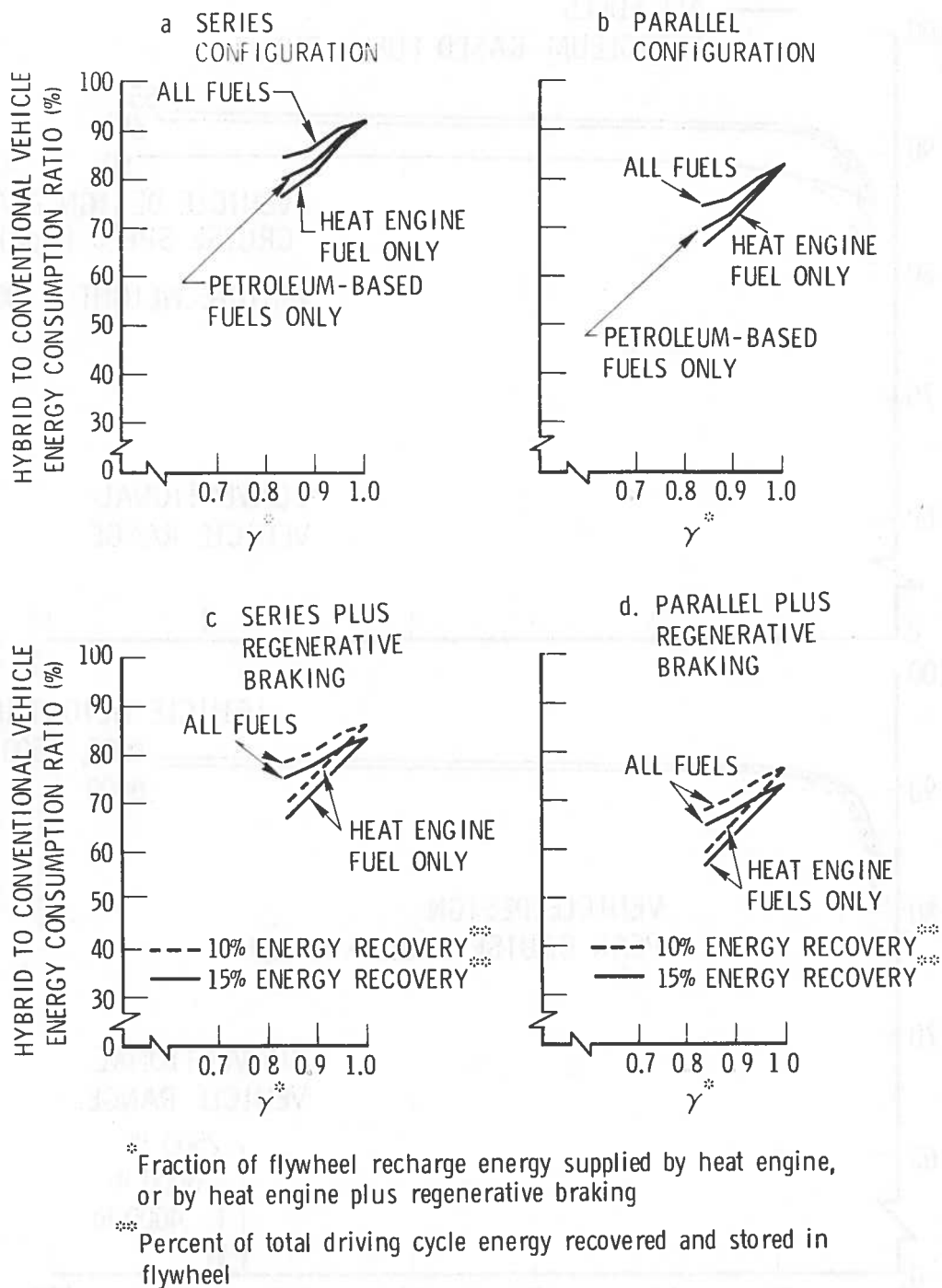


FIGURE 10-113. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA URBAN DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

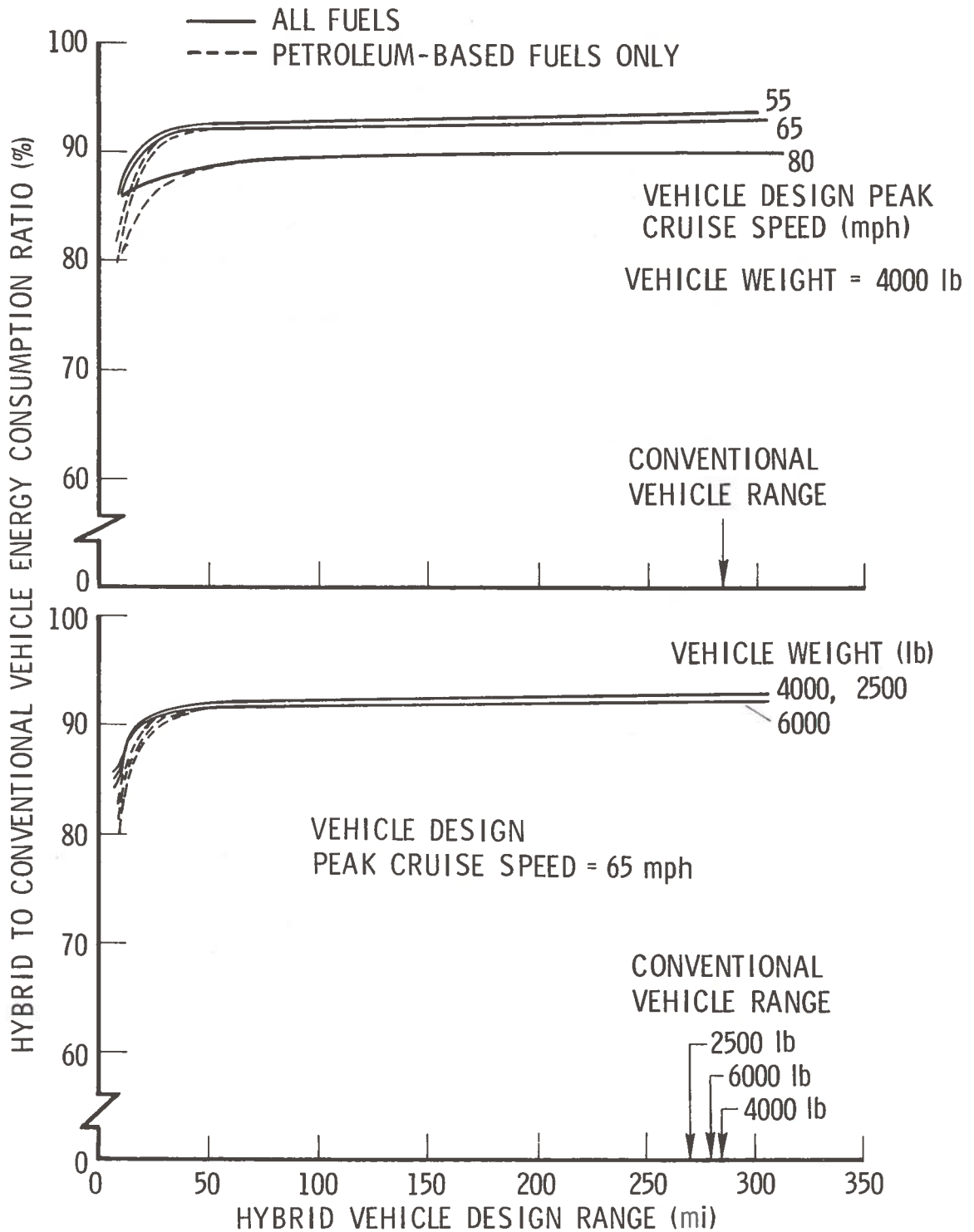


FIGURE 10-114. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, SERIES CONFIGURATION

100.

EFFICIENCY (%)

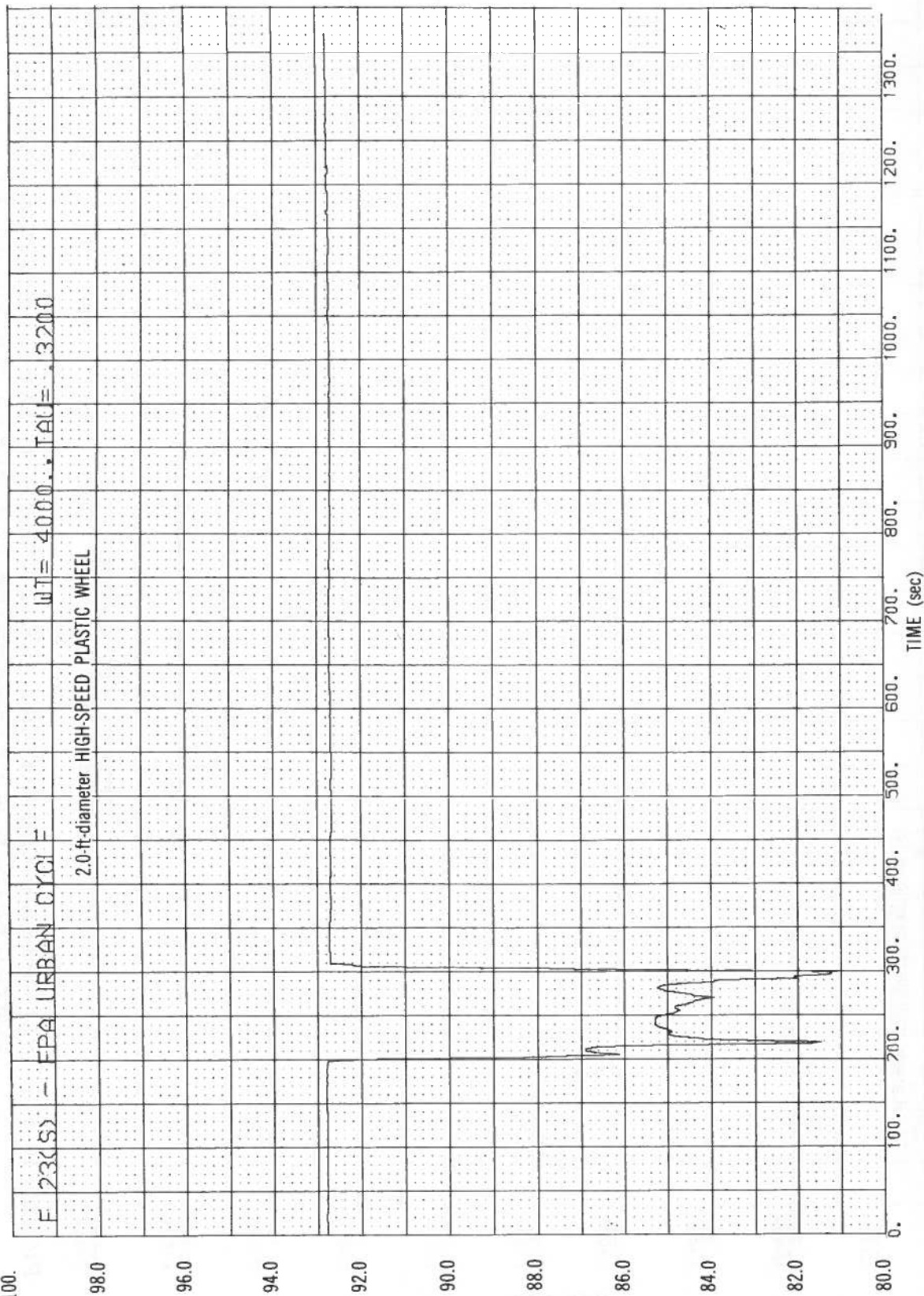


FIGURE 10-115. TRANSMISSION T2 EFFICIENCY HISTORY (ENGINE-FLYWHEEL LINK): HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, 2.0-FT-DIAMETER HIGH-SPEED PLASTIC WHEEL, EPA URBAN DRIVING CYCLE, $\tau = 0.32$

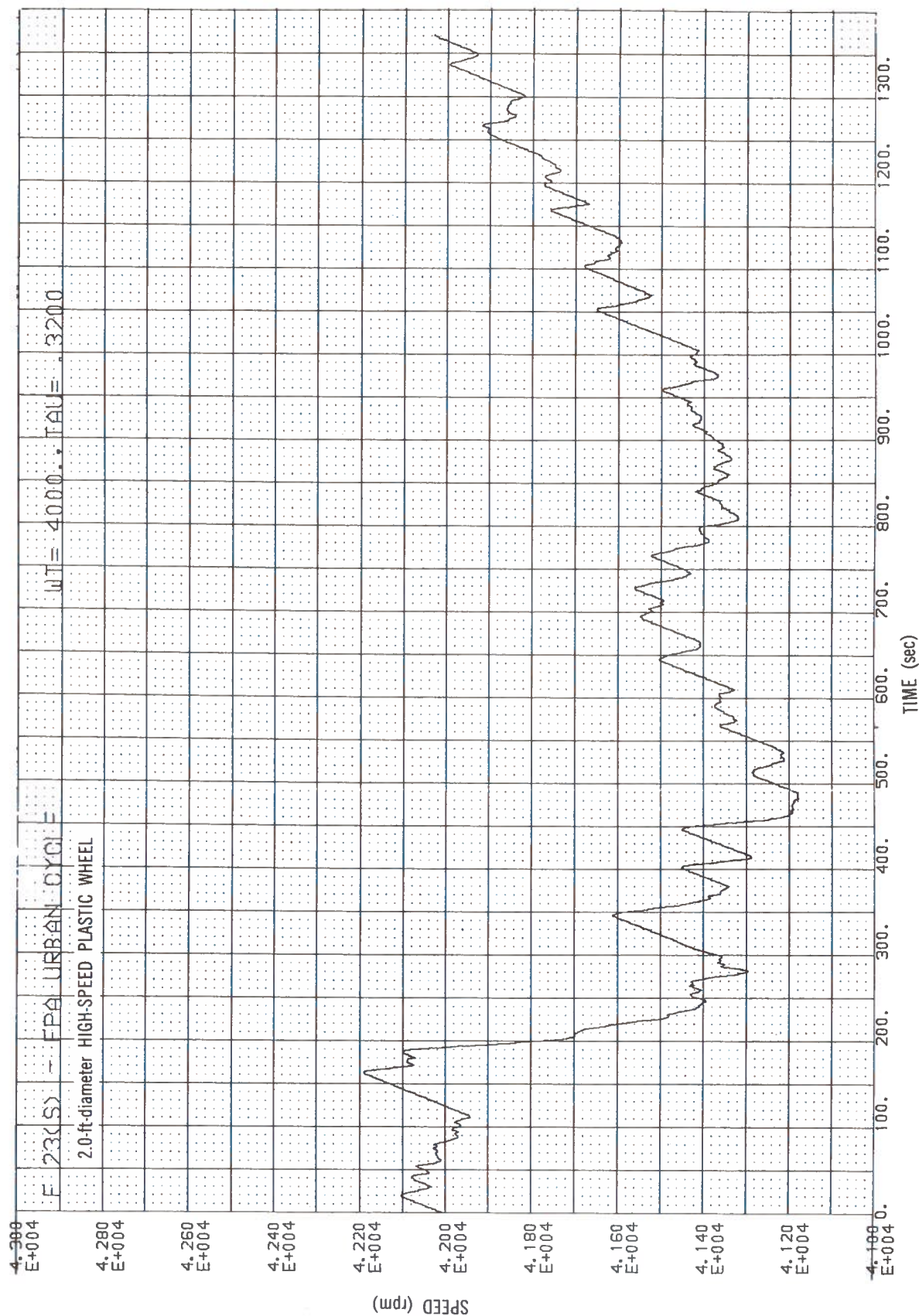


FIGURE 10-116. FLYWHEEL SPEED HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, 2.0-FT-DIAMETER HIGH-SPEED PLASTIC WHEEL, EPA URBAN DRIVING CYCLE, $\tau = 0.32$

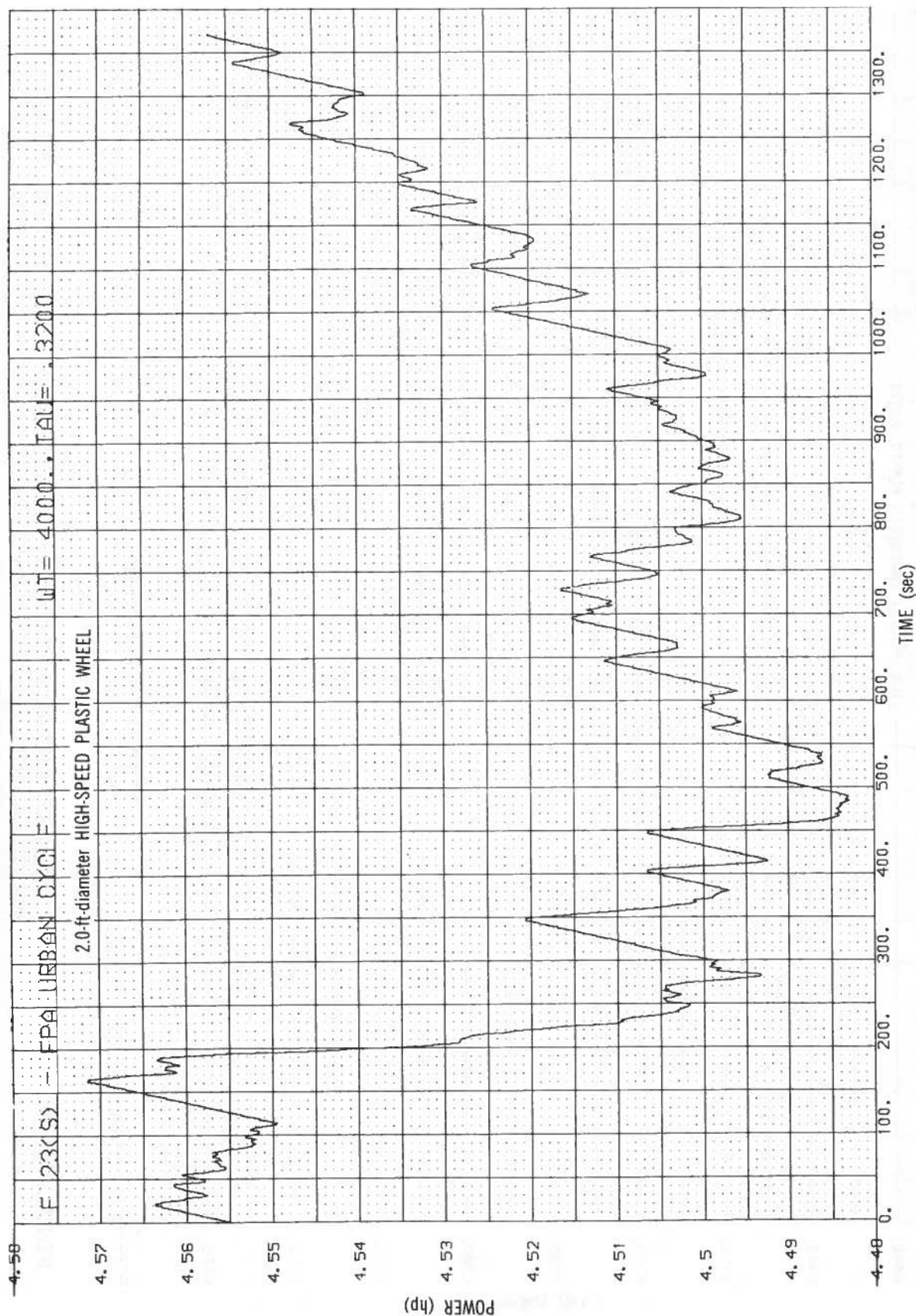


FIGURE 10-117. FLYWHEEL PARASITIC POWER LOSS HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, 2.0-FT-DIAMETER HIGH-SPEED PLASTIC WHEEL, EPA URBAN DRIVING CYCLE, $\tau = 0.32$

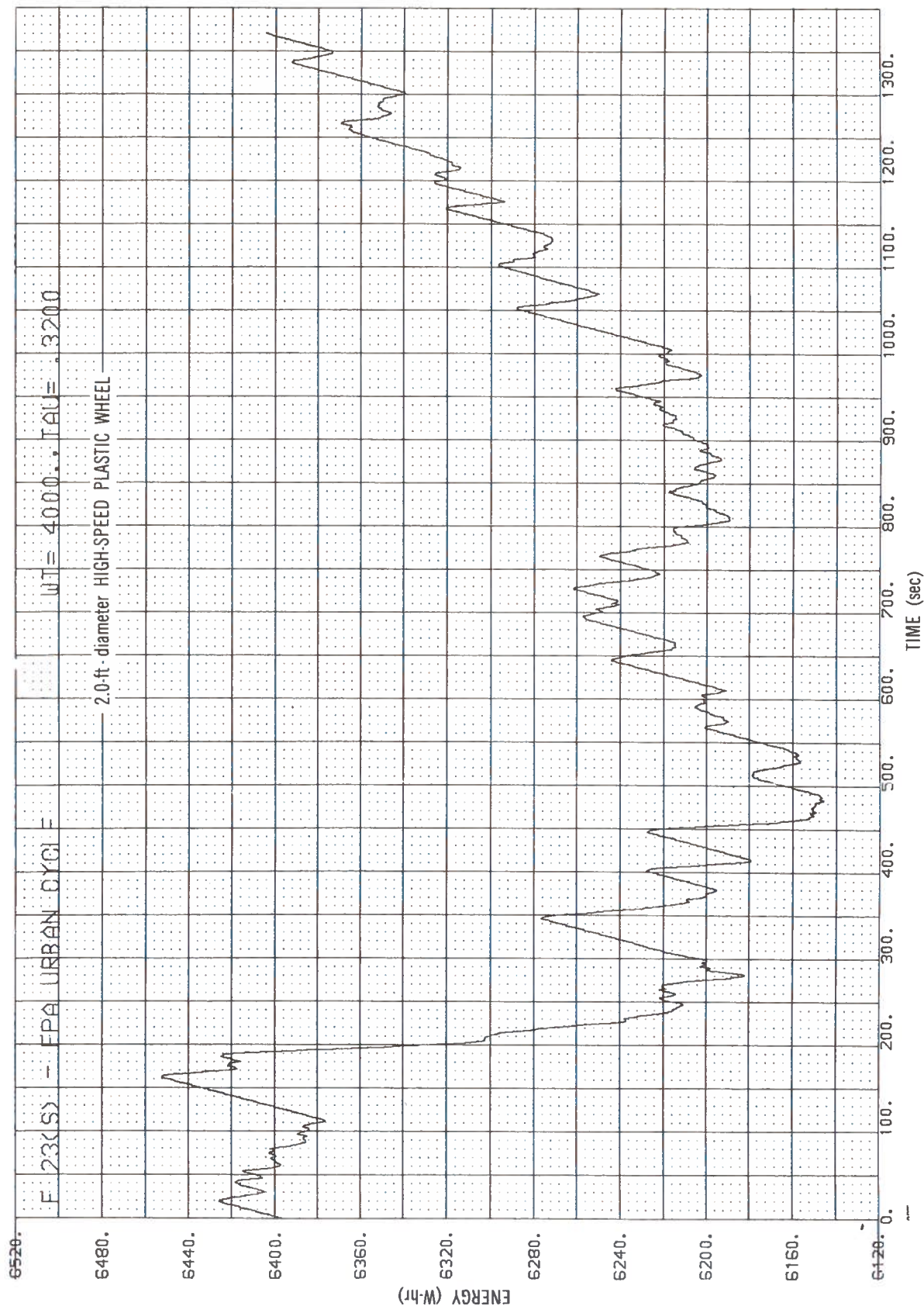


FIGURE 10-118. FLYWHEEL STORED ENERGY HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, 2.0-FT-DIAMETER HIGH-SPEED PLASTIC WHEEL, EPA URBAN DRIVING CYCLE, $\tau = 0.32$

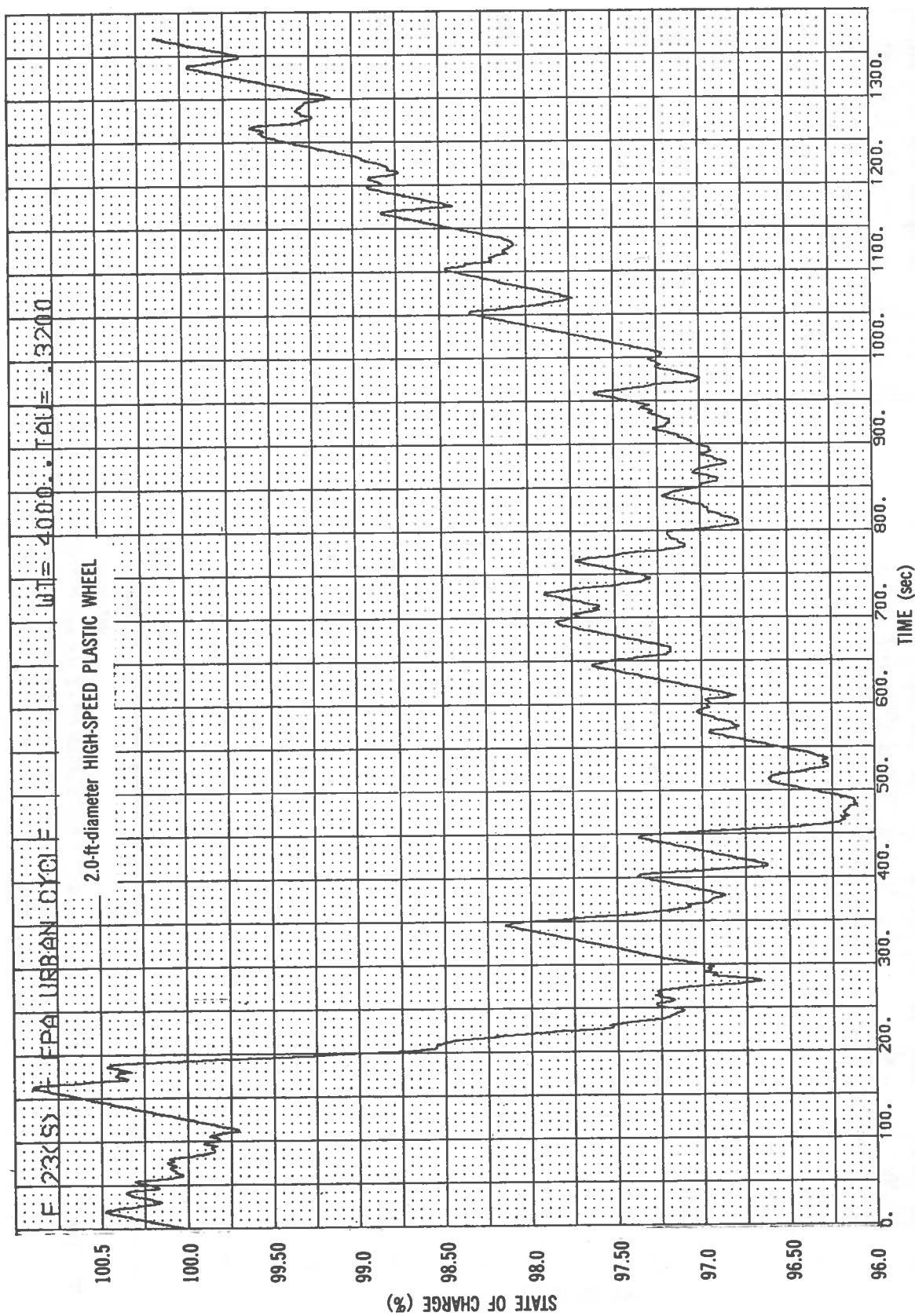


FIGURE 10-119. FLYWHEEL STORED/INITIAL ENERGY HISTORY: HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, 2.0-FT-DIAMETER HIGH-SPEED PLASTIC WHEEL, EPA URBAN DRIVING CYCLE, $\tau = 0.32$

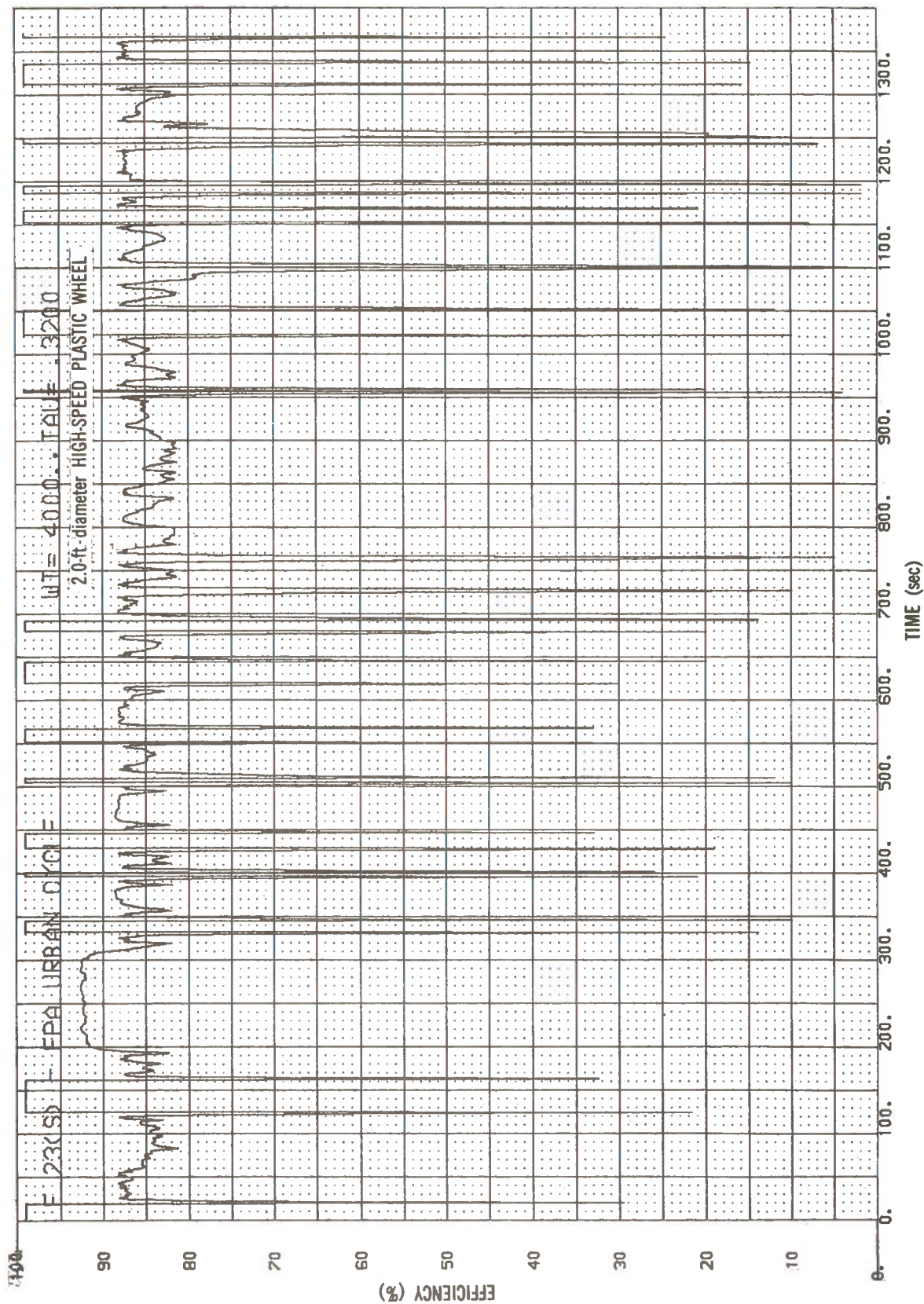


FIGURE 10-120. TRANSMISSION T3 EFFICIENCY (FLYWHEEL-VEHICLE DRIVE WHEELS LINK):
HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, 2.0-FT -
DIAMETER HIGH-SPEED PLASTIC WHEEL, EPA URBAN DRIVING CYCLE, $\tau = 0.32$

VEHICLE DESIGN PEAK CRUISE SPEED = 65 mph
VEHICLE WEIGHT = 4000 lb
SERIES CONFIGURATION

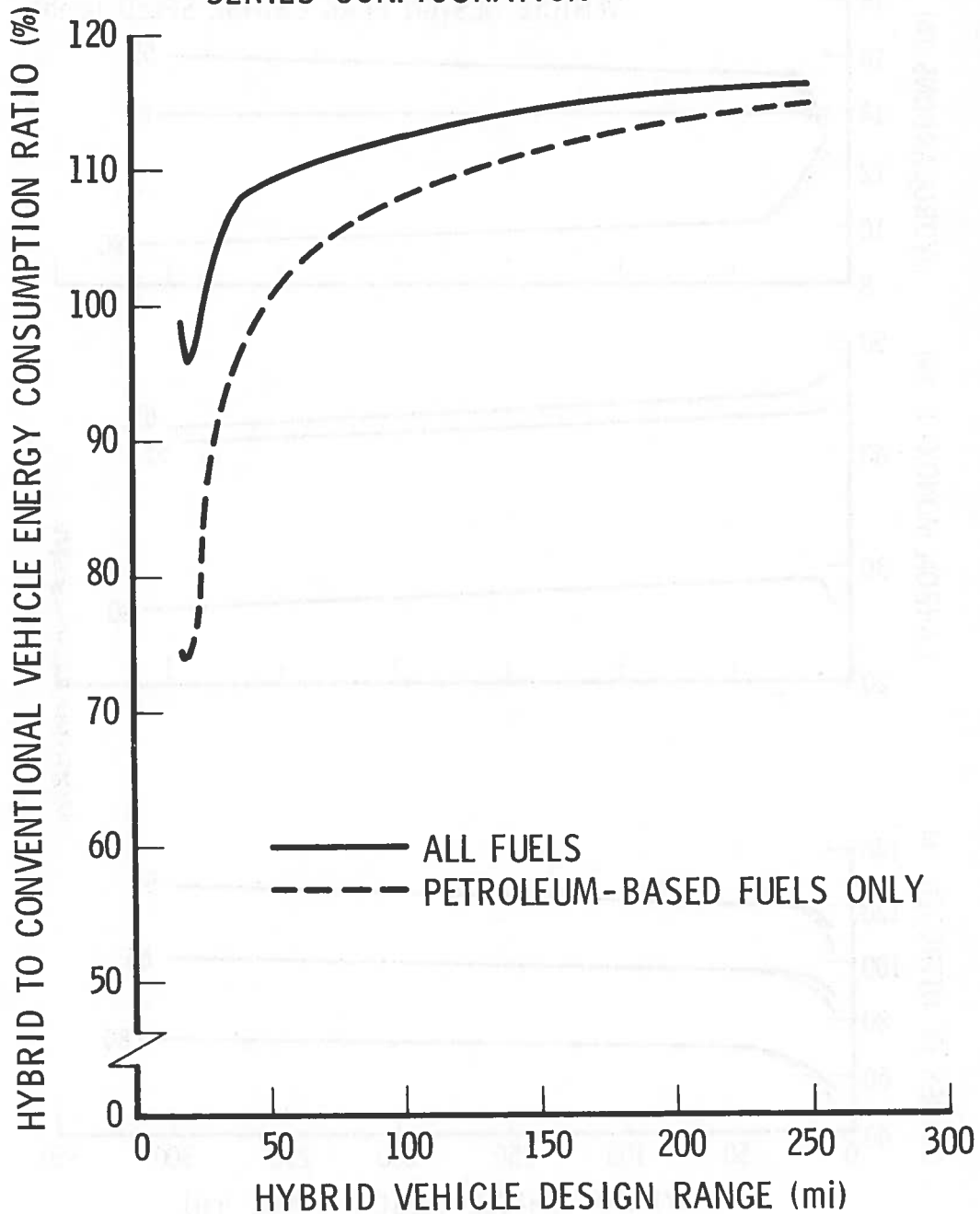


FIGURE 10-121 HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED ENERGY CONSUMPTION: EPA URBAN DRIVING CYCLE, 2.0-FT-DIAMETER HIGH-SPEED PLASTIC COMPOSITE ROTOR

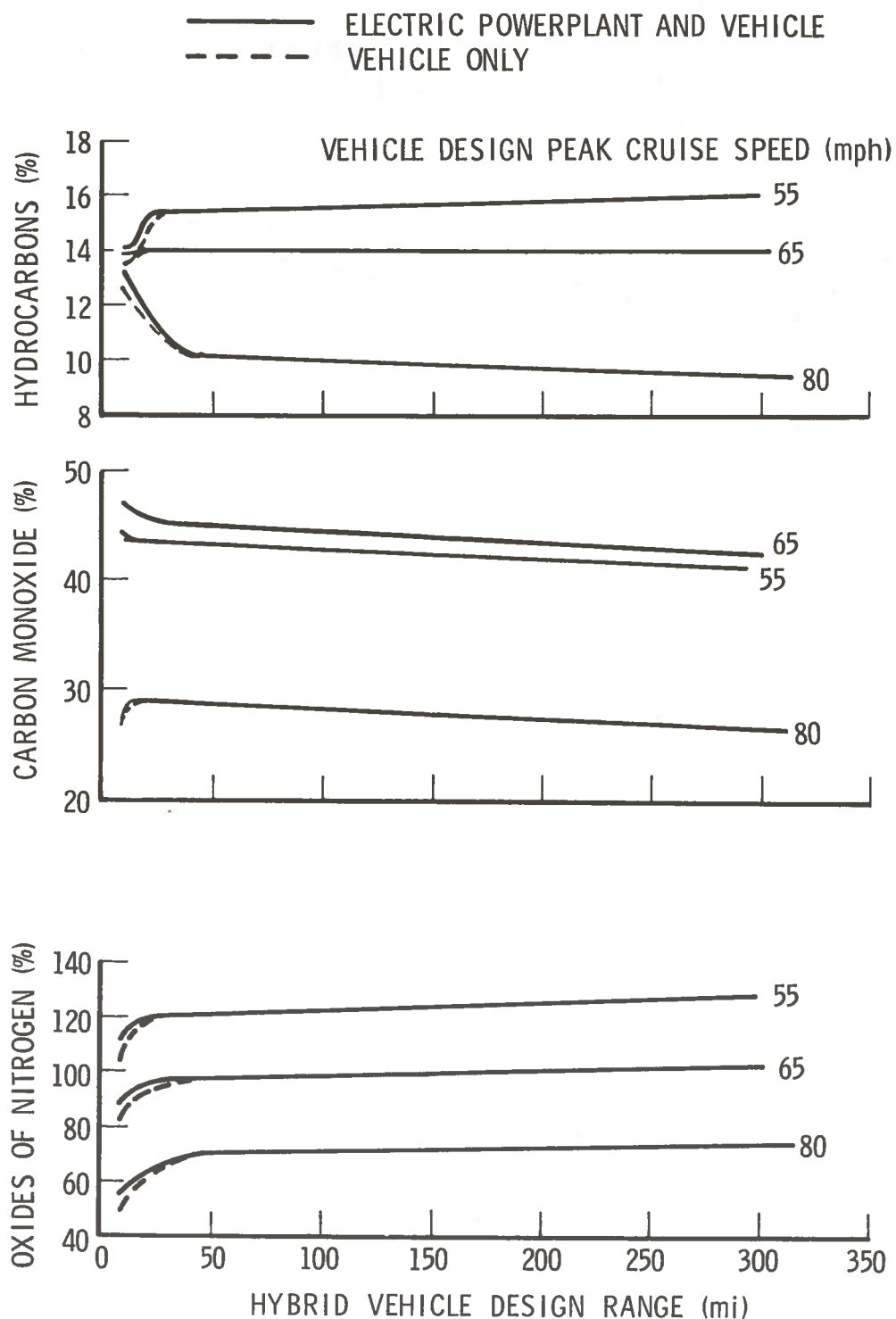


FIGURE 10-122. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE WEIGHT = 4000 LB, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

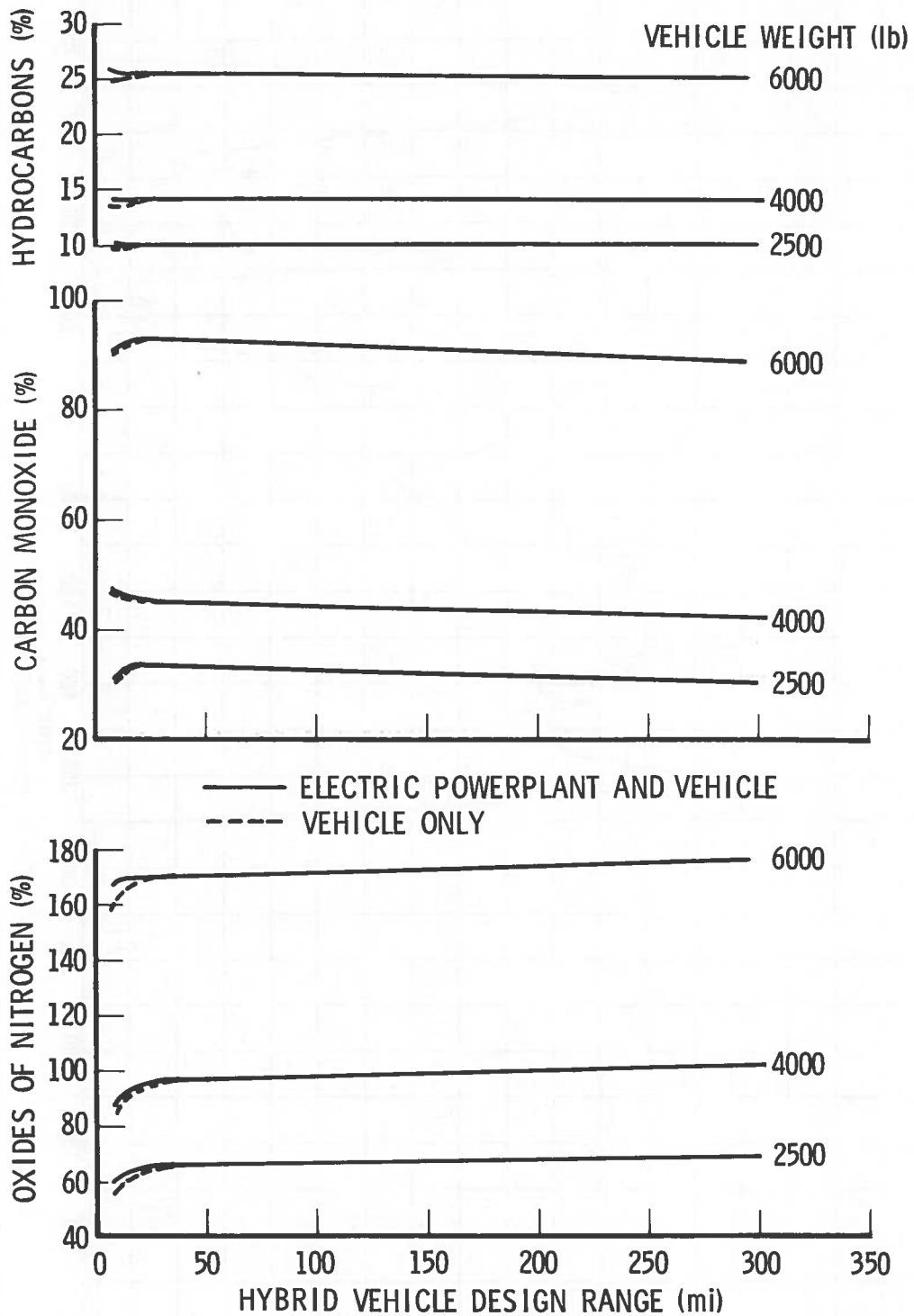


FIGURE 10-123. HYBRID HEAT ENGINE/FLYWHEEL VEHICLE-RELATED EXHAUST EMISSIONS: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION (REF.: 1975-76 FEDERAL STANDARDS)

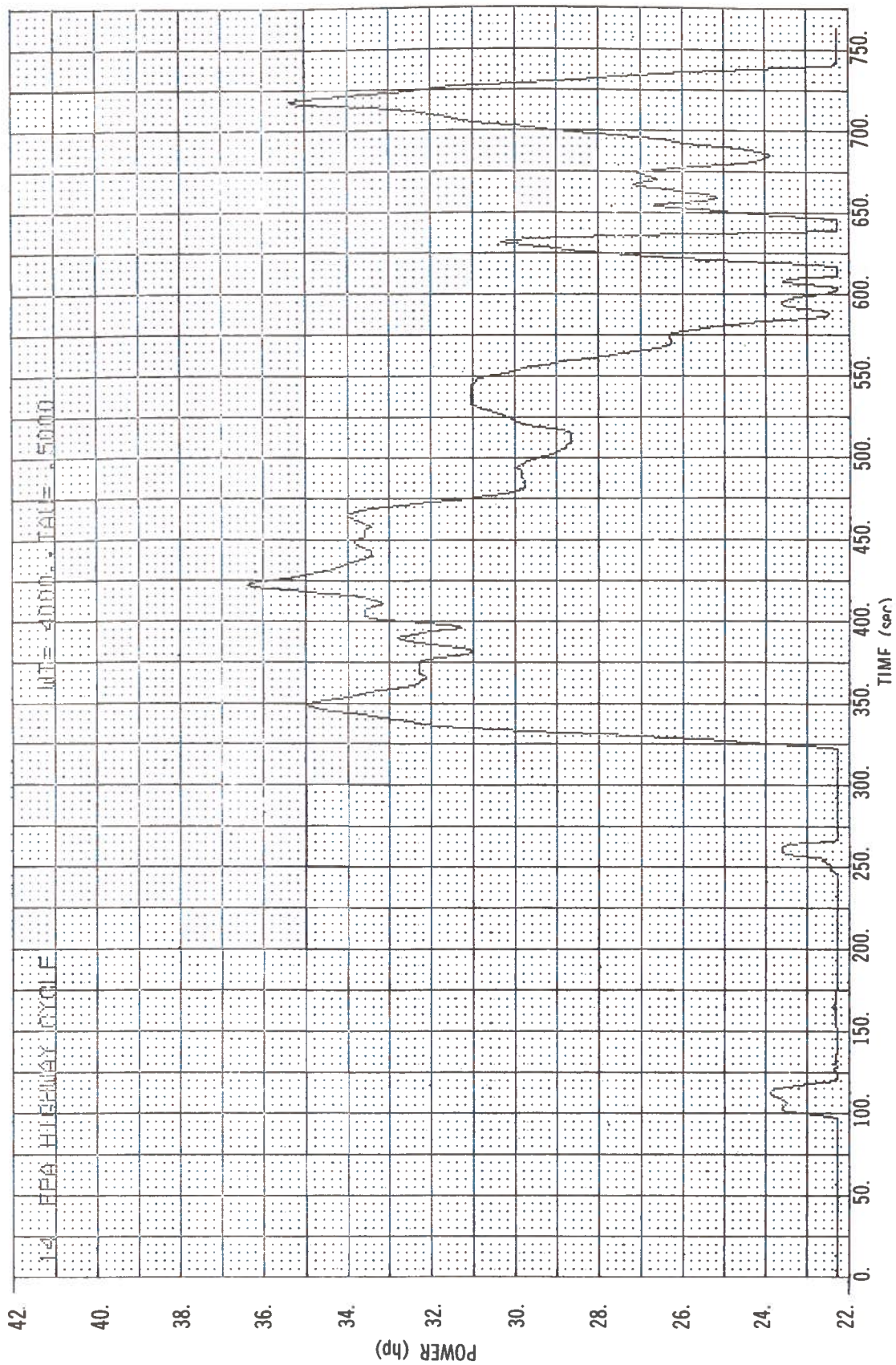


FIGURE 10-124. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE / FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA HIGHWAY DRIVING CYCLE, $\tau = 0.5$

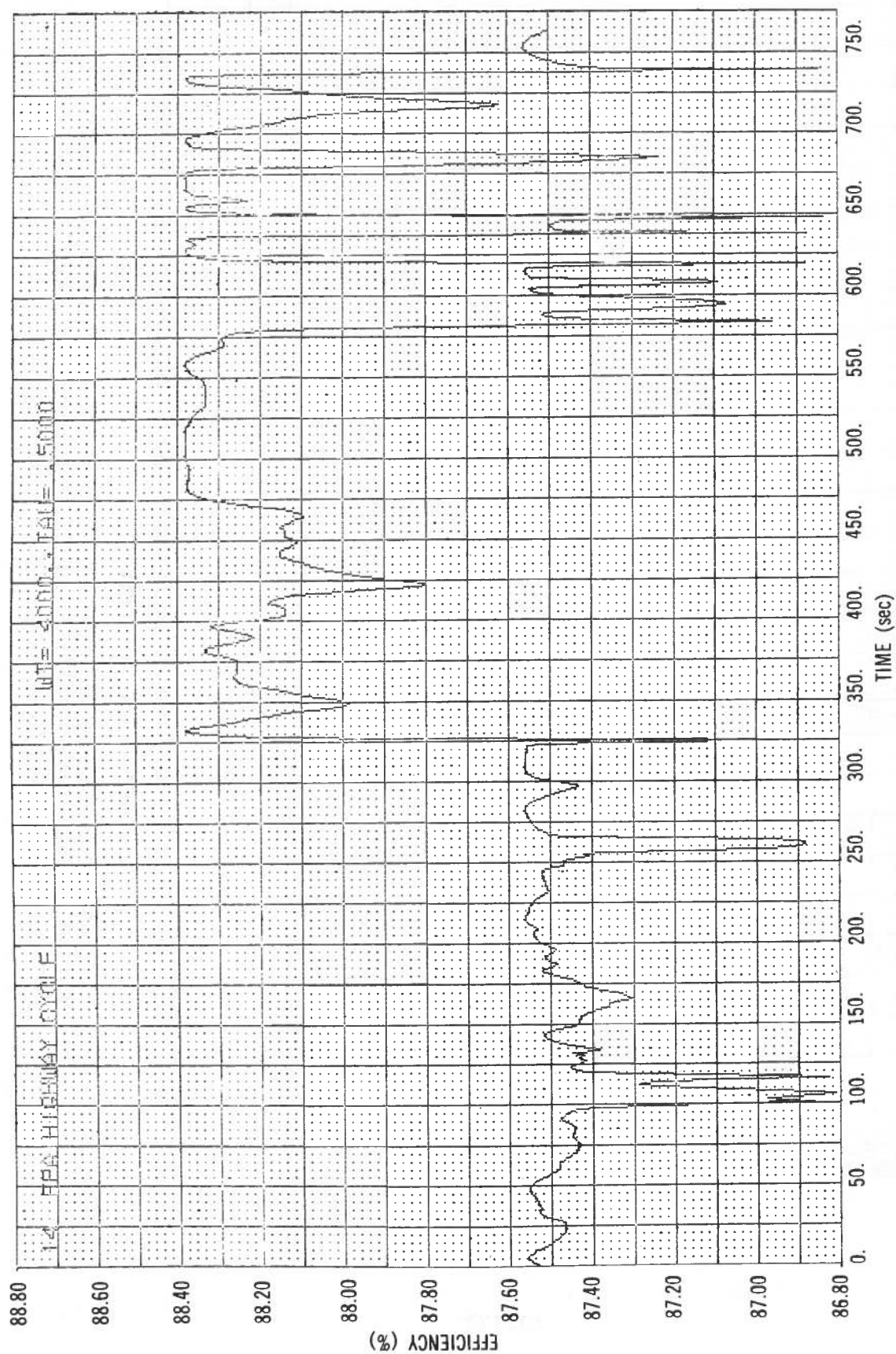


FIGURE 10-125. TRANSMISSION T2 EFFICIENCY HISTORY (ENGINE-FLYWHEEL LINK):
HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA
HIGHWAY DRIVING CYCLE, $\tau = 0.5$

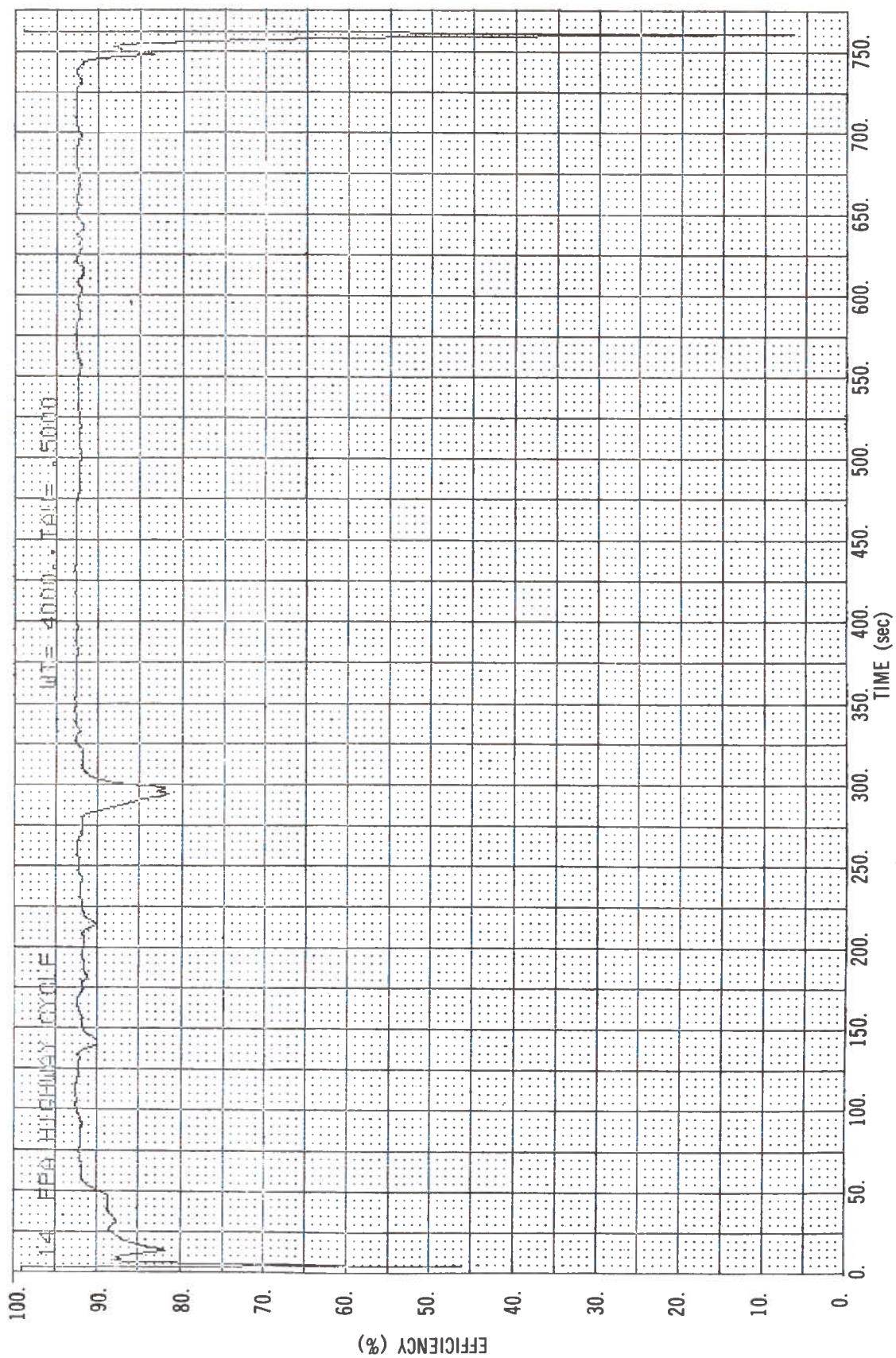
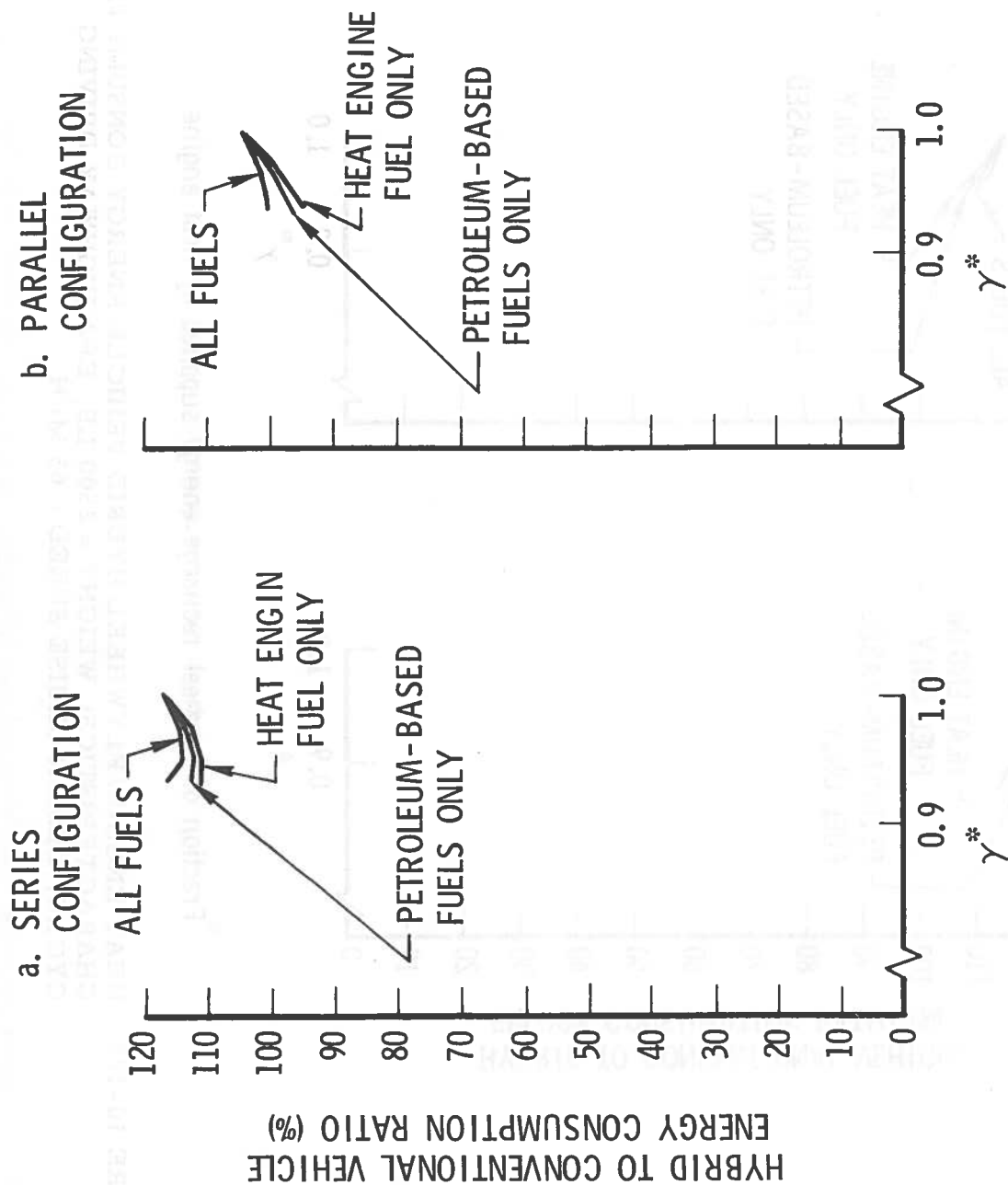
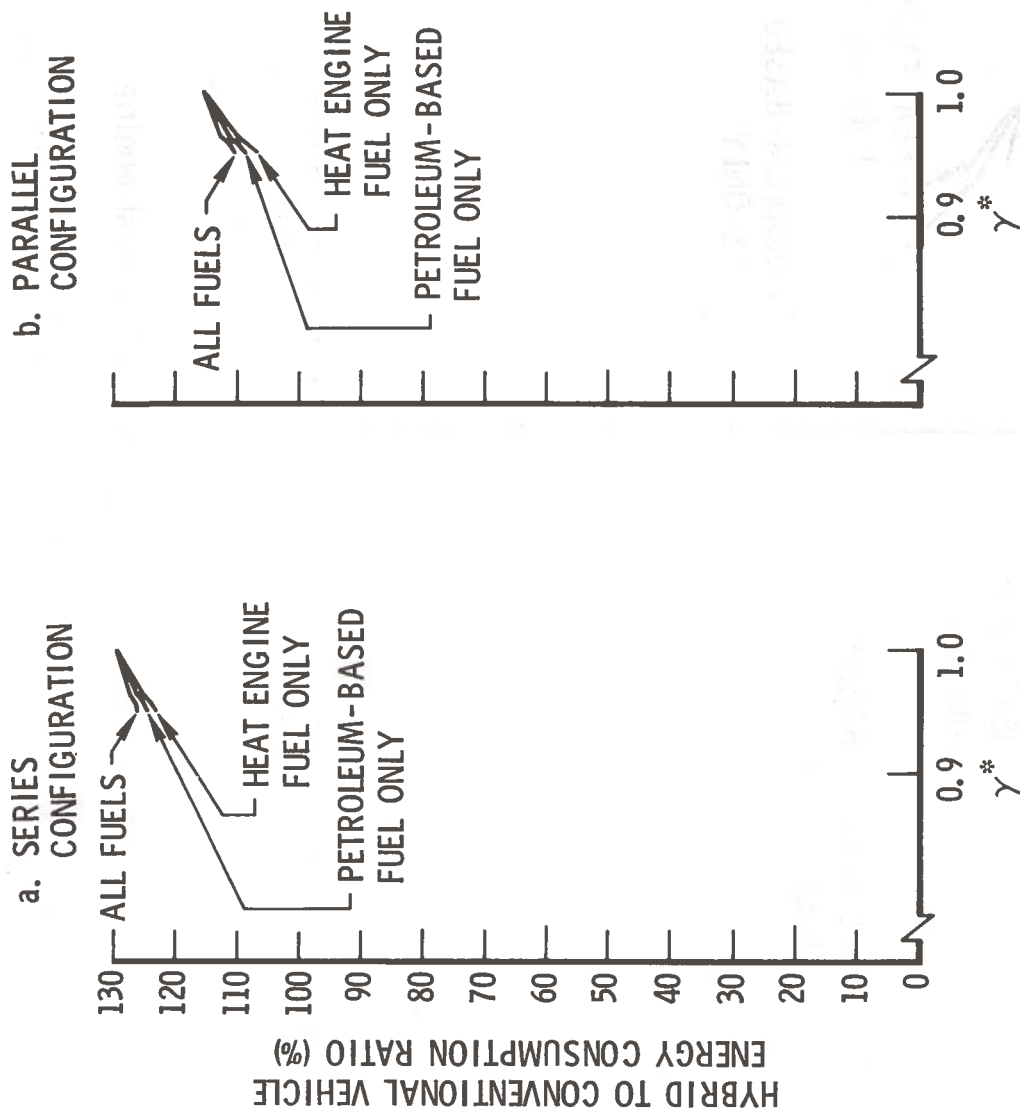


FIGURE 10-126. TRANSMISSION T3 EFFICIENCY HISTORY (FLYWHEEL-VEHICLE DRIVE WHEELS LINK): HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION, EPA HIGHWAY DRIVING CYCLE, $\tau = 0.5$



*Fraction of flywheel recharge energy supplied by heat engine

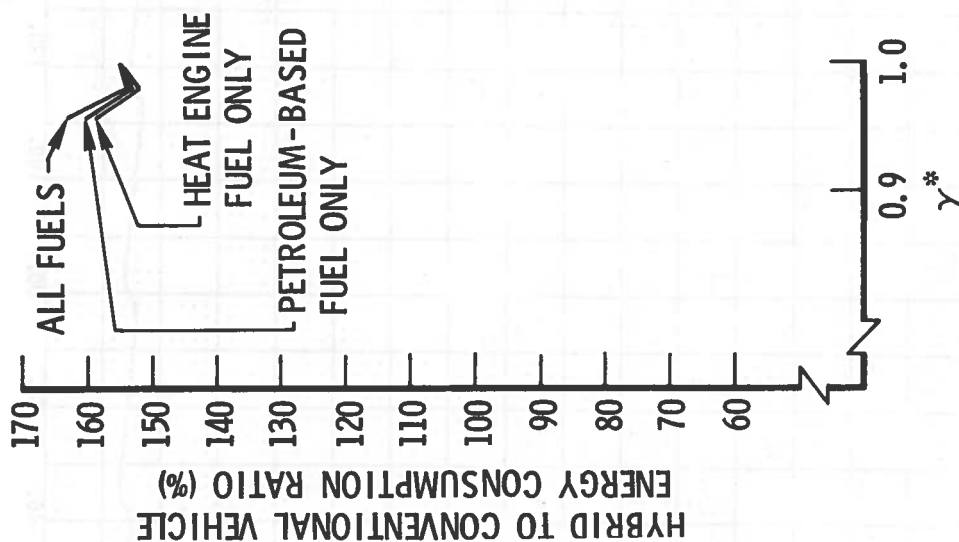
FIGURE 10-127. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



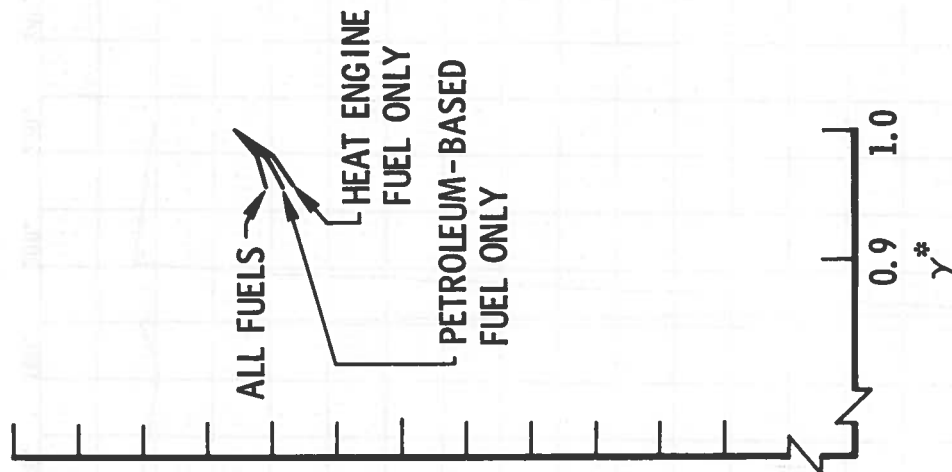
*Fraction of flywheel recharge energy supplied by heat engine

FIGURE 10-128. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 2500 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

a. SERIES CONFIGURATION



b. PARALLEL CONFIGURATION



* Fraction of flywheel recharge energy supplied by heat engine

FIGURE 10-129. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, EPA HIGHWAY DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

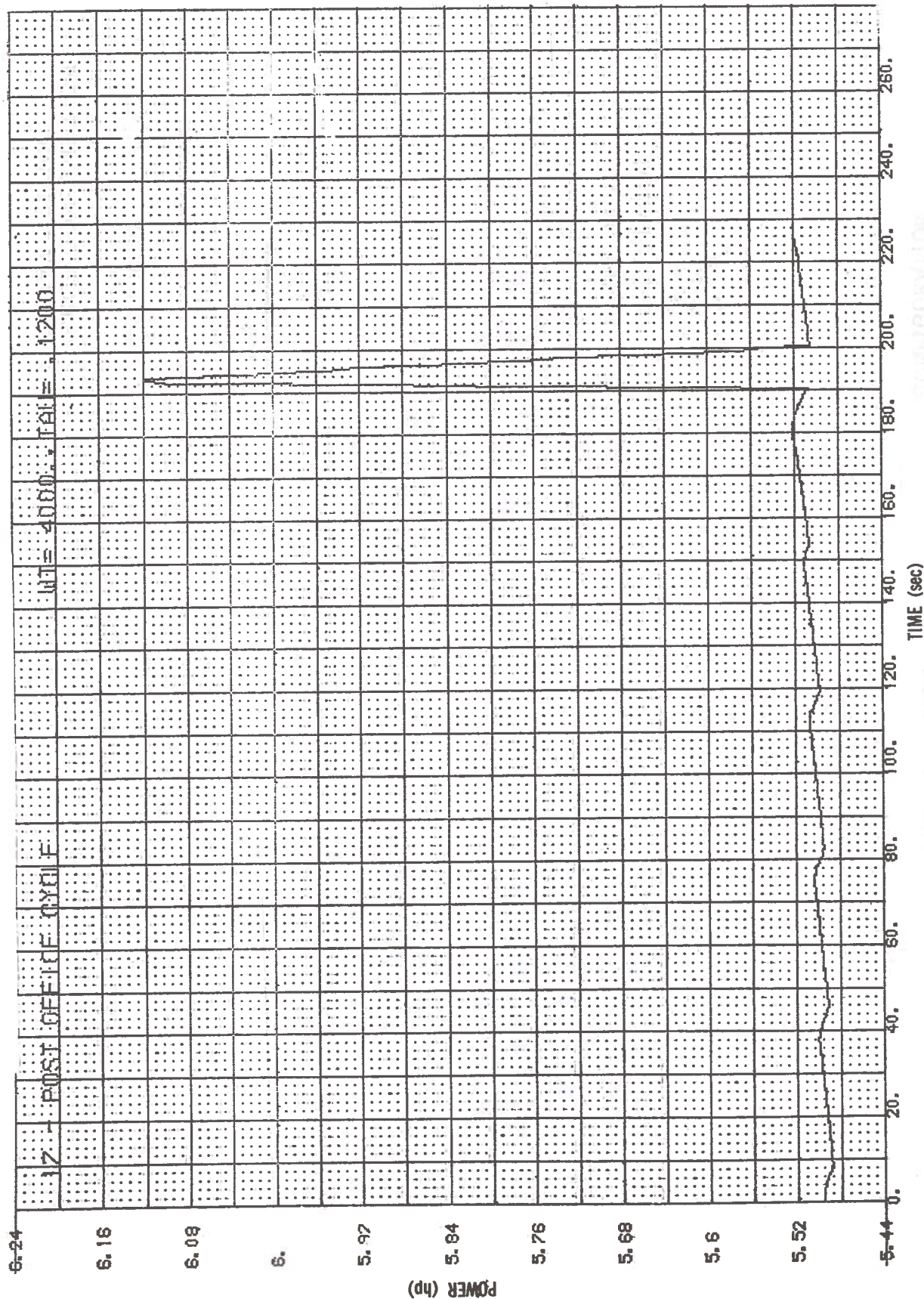


FIGURE 10-130. ENGINE PROPULSION POWER OUTPUT HISTORY: HEAT ENGINE/FLYSHEEL SYSTEM, SERIES CONFIGURATION, U.S. POSTAL SERVICE DELIVERING 2000.

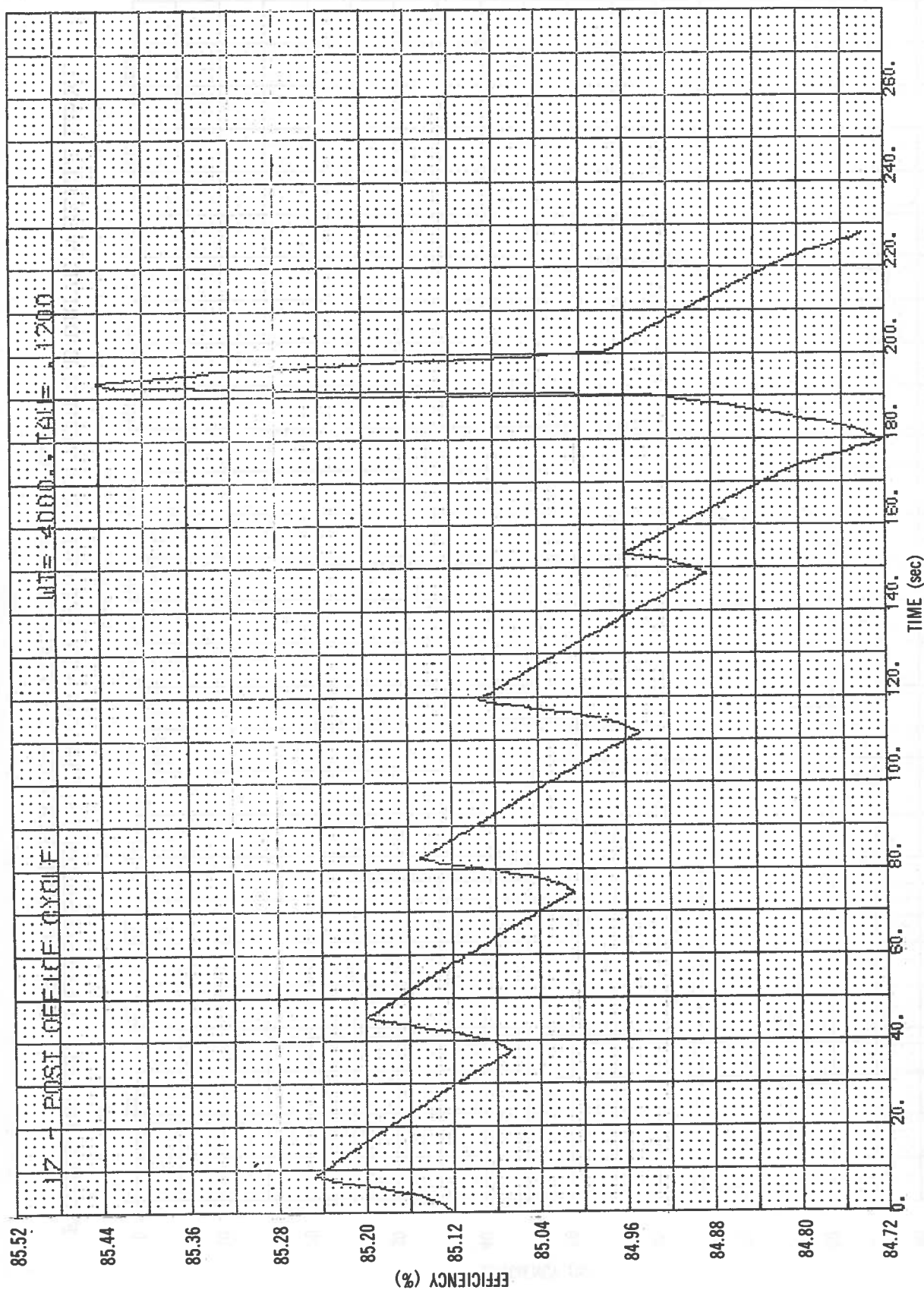


FIGURE 10-131. TRANSMISSION T2 EFFICIENCY HISTORY (ENGINE-FLYWHEEL LINK):
HEAT ENGINE/FLYWHEEL SYSTEM, SERIES CONFIGURATION,
U.S. POSTAL SERVICE DRIVING CYCLE, $\tau = 0.12$

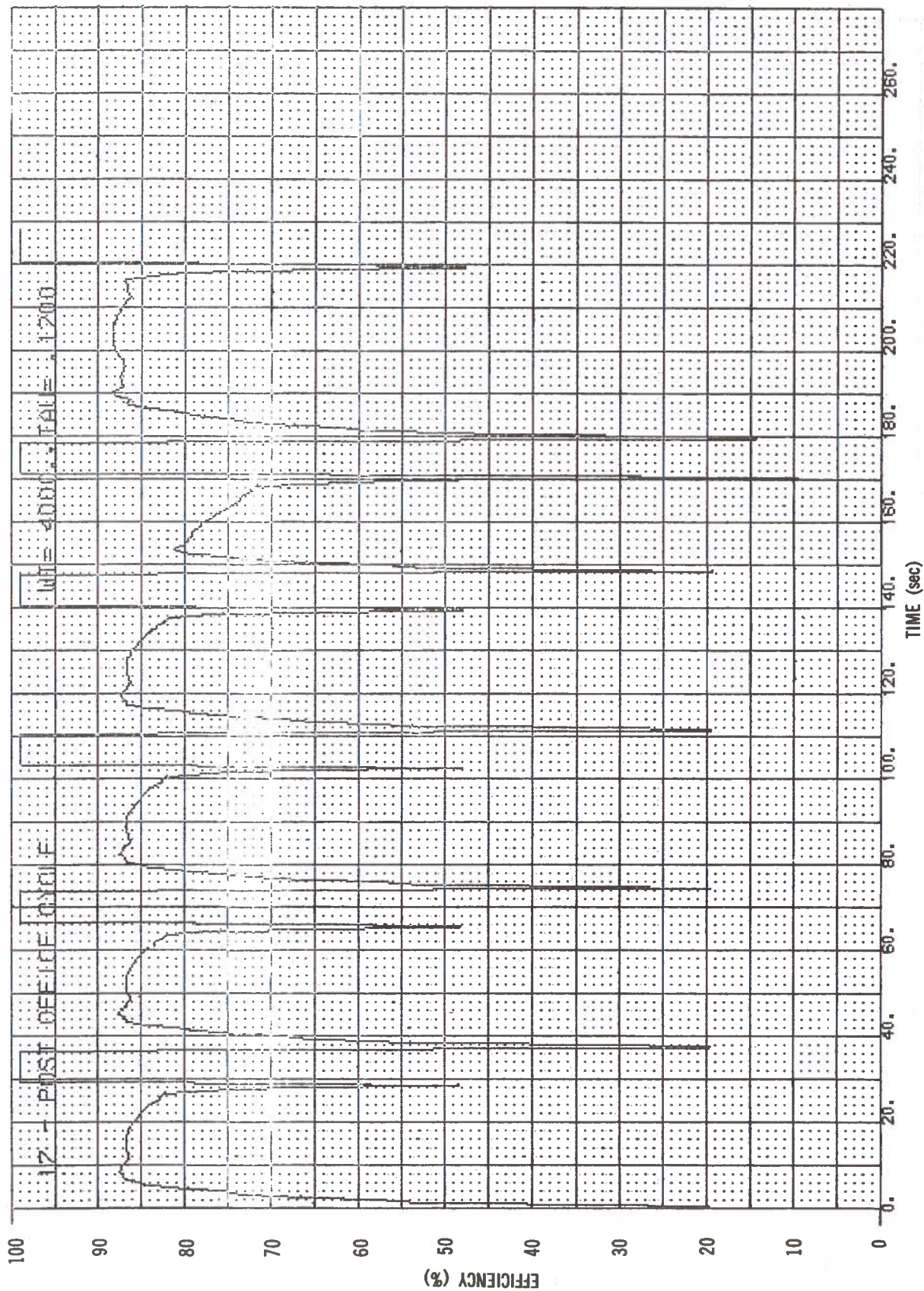
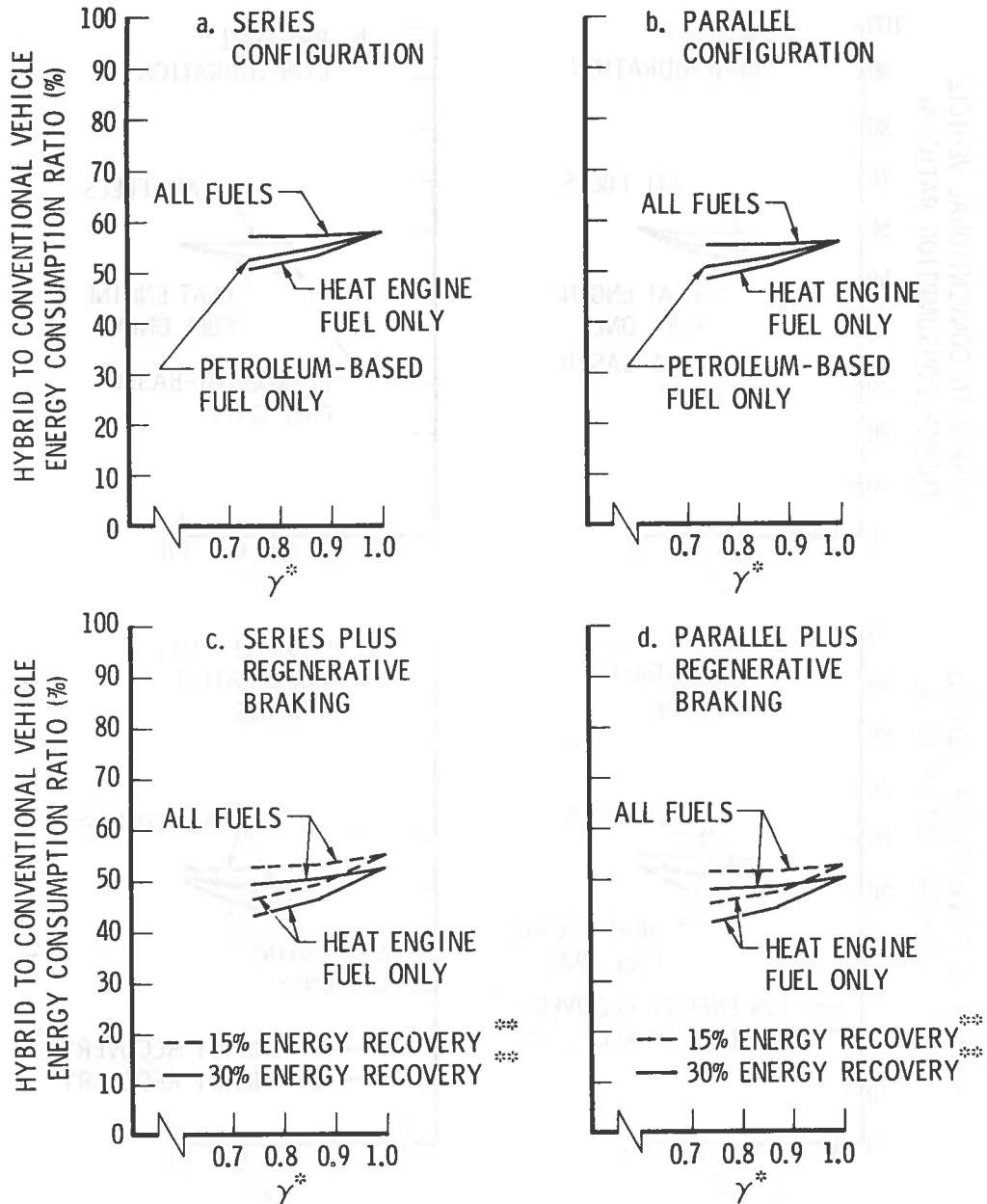


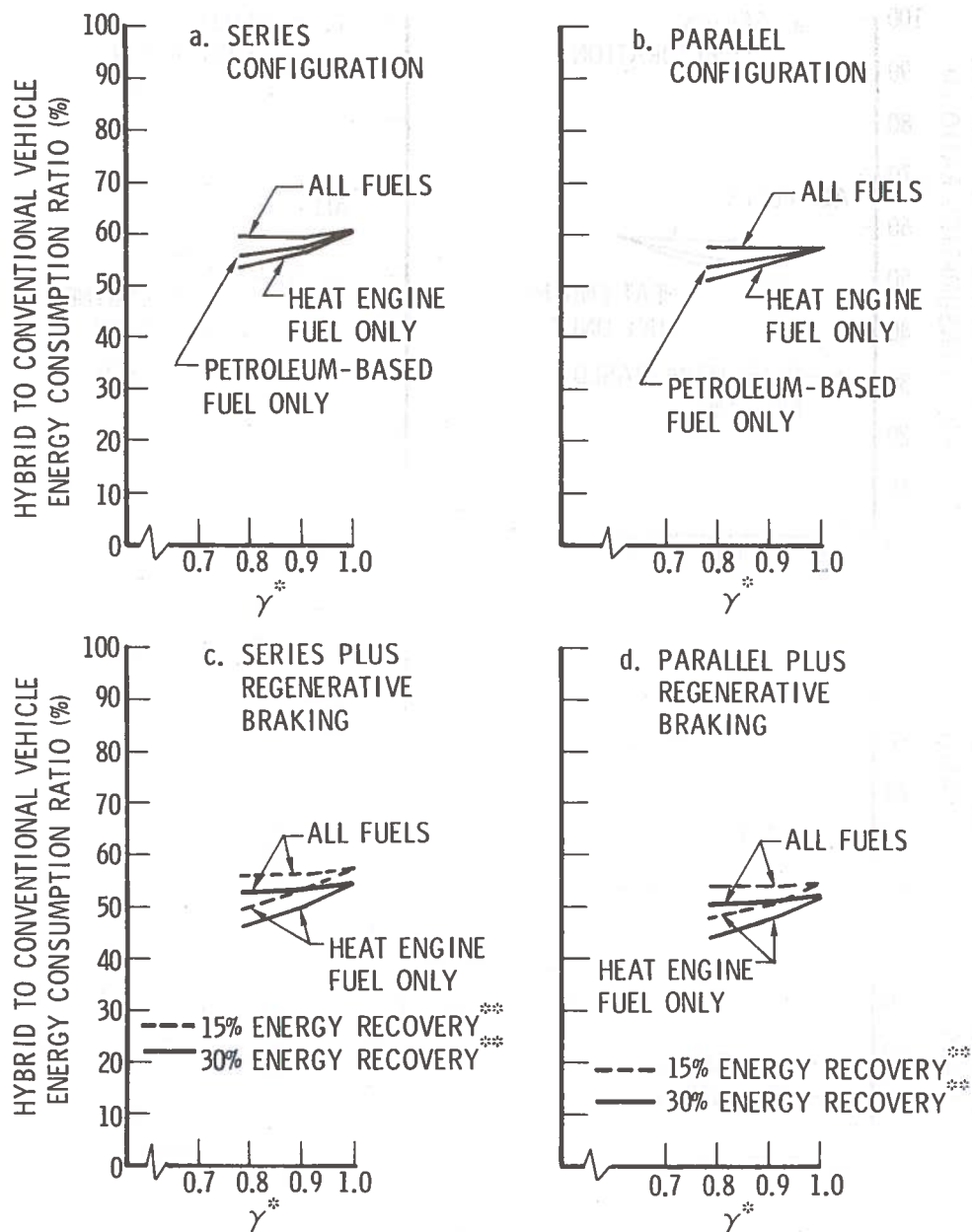
FIGURE 10-132. TRANSMISSION T3 EFFICIENCY (FLYWHEEL-VEHICLE DRIVE WHEELS LINK),
U.S. POSTAL SERVICE DRIVING CYCLE, $\tau = 0.12$



* 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

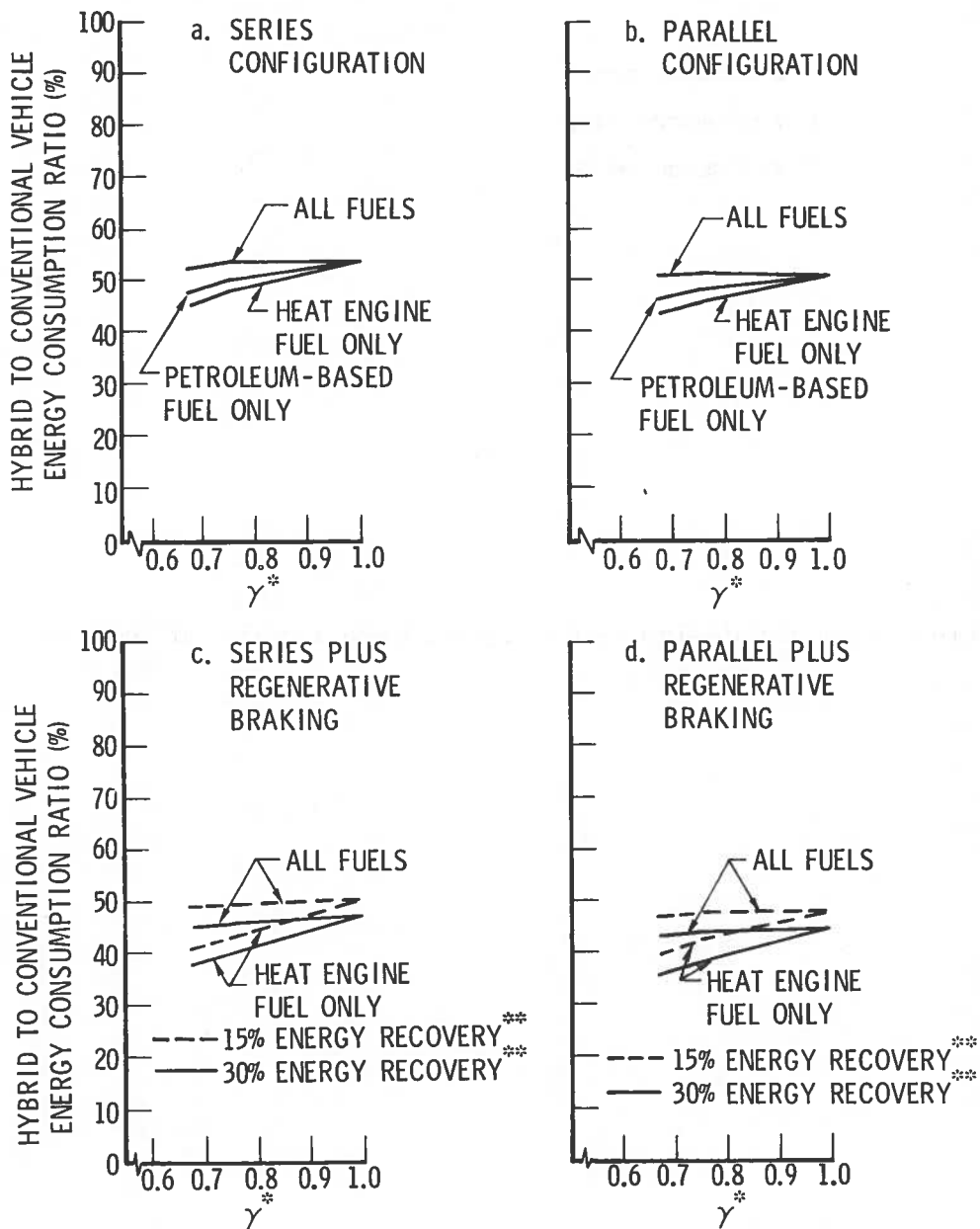
FIGURE 10-133. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 4000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH



* 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 10-134. 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 10-135. HEAT ENGINE/FLYWHEEL HYBRID VEHICLE ENERGY CONSUMPTION CHARACTERISTICS: WEIGHT = 6000 LB, U.S. POSTAL SERVICE DRIVING CYCLE, DESIGN CRUISE SPEED = 65 MPH

11. HYBRID VEHICLE APPLICATIONS AND POTENTIAL FOR ENERGY SAVINGS

The results presented in Section 10 show that hybrid vehicle energy consumption and emissions are highly dependent on the characteristics used for each powertrain component and on the road performance (cruise speed or acceleration) specified for a given weight vehicle. Furthermore, the results also reflect (a) the continuous rather than discontinuous form of engine operation, (b) the particular balance between fuel consumption and emissions that was selected from the engine characteristics map, and (c) the nonoptimization of system operation at each discrete value of γ , vehicle weight, or design peak cruise speed.

With a myriad of options available to the vehicle designer, the present study results represent only a partial view of the potential for energy and/or emissions savings with hybrid vehicles. Therefore, the intent in the subsequent discussion is not to show a "best" design approach for a given application, but rather to point out trends that have been revealed through the analyses presented in Sections 9 and 10 for the particular systems selected in this study.

11.1 HEAT ENGINE/BATTERY HYBRID VEHICLES

The series configuration with nickel-zinc batteries housed in a full-performance, full-size, 4000-lb car can provide energy savings in applications that do not require cruise speeds in excess of 65 mph and do not require daily operating ranges in urban driving much beyond 100 to 150 miles. The operating range of 100 miles is based on saving all types of fuel (oil, gas, coal, and nuclear), whereas the operating range of 150 miles is based on saving petroleum-based fuel (oil and gas). However, a more stringent restriction on vehicle design operating range is needed to meet the 1975-76 federally mandated emission standards for NO_x (HC and CO are no problem, being just small fractions of the standards). This impact narrows the design operating range to 100 to 125 miles, depending upon whether the electric generating plant is in the air quality region (about 100 miles) or outside the air quality region (about 125 miles). At the lower range, the energy savings is about

5 percent for all fuels and 15 percent for petroleum-based fuels, when compared with a conventionally powered car. Therefore, this type of vehicle appears to be well suited for efficiently meeting most of the personal urban transportation needs for up to six passengers.

The addition of regenerative braking capability to the vehicle powertrain can relieve these range restrictions to varying degrees. A recovery of 15 percent of vehicle energy expended at the drive wheels can provide energy savings at a design operating range in excess of 300 miles, although the impact of NO_x emission continues to limit the range to about 150 miles.

The more complex parallel configuration powertrain in a 4000-lb car, when combined with a regenerative braking system that recovers 15 percent of drive wheel energy, can result in energy savings of better than 15 percent compared to a conventionally powered car, and design operating range restrictions would be nonexistent even when considering the requirement to meet NO_x emission standards.

Vehicle weight and design cruise speed have a major impact on potential for energy savings. Generally the heavier vehicles with lower design cruise speeds can be expected to produce the greatest savings. Unfortunately, heavier vehicles produce greater emissions and would have difficulty meeting the NO_x emission standards.

Vehicle design has a marked effect on possible energy savings. The bluff, high drag, body of a delivery van can be expected to have significantly greater energy expenditure and exhaust emissions than the equivalent weight automobile.

Increased reliance on electric wall power (supplied by stationary electric generating plants) for battery recharging 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.

If the hybrid vehicle were introduced at an early date, then possibly only lead-acid batteries could be used. For a series configuration under these conditions, design operating ranges that result in energy savings are restricted to about 100 to 125 miles -- similar to when NO_x emissions are the controlling factor.

Although the nickel-zinc batteries considered in this study have a specific energy of only 22 W-hr/lb (see Section 5.3), further development

is expected to increase this measure of performance to about 35 W-hr/lb (see Section 4.3). When combined with (a) the given allowable powertrain weight, (b) the design weight of all components except the battery, and (c) the system voltage, the specific energy sets the battery capacity. This capacity will have a very significant effect on vehicle design operating range when the heat engine does not provide full battery recharging. In this respect, the higher specific energy would improve operating range. Alternatively, a reduction in allowable powertrain weights from those values assumed in this study would reduce the range.

Relaxation of vehicle design performance requirements for cruise speed has the effect of reducing electric drive motor and heat engine/generator size with the result that more weight and volume are available for batteries, thereby improving potential operating range. However, a drawback to this approach is that the smaller engine in a fixed weight vehicle designed for reduced cruise speed seems to produce more NO_x emissions. This effect could nullify the range extension for cases where NO_x emissions restrict the design operating range. Reduced acceleration, though, is expected to produce positive results for both energy and emissions because this change in performance would reduce the size of only the electric drive motor.

An additional impact on vehicle range would result if fuel tank capacity were to be reduced when greater reliance is placed on electric outlet power for battery recharging. In other words, at low values of γ , where engine power is low, fuel consumed is less, and the fuel tank capacity can be lowered. The weight saving could then be transferred to additional weight available for batteries, thereby improving vehicle range.

Use of the hybrid heat engine/battery vehicle in high-speed highway driving is generally a poor application. The analysis results indicate much greater energy consumption and emissions for the series configuration hybrid than found with conventionally powered vehicles. Only a parallel hybrid powertrain configuration could be expected to provide comparable energy consumption and emissions, but to achieve this result the design operating range is curtailed and would not necessarily be compatible with high-speed highway vehicle needs.

On the basis of limited evidence, the most favorable application of the heat engine/battery hybrid vehicle would be to low-speed, stop-and-go driving that is characteristic of certain types of delivery services (e.g., mail or milk delivery in residential neighborhoods). Under this type of driving schedule, conventionally powered vehicles consume excessive fuel due to poor engine brake specific fuel consumption (pounds per horsepower-hour) and to extensive idle fuel consumption. The use of regenerative braking with hybrid vehicles would also prove most favorable for repetitive stop-and-go driving.

Introduction of the heat engine/battery hybrid vehicle into the consumer market would initially prove to be most advantageous in the Pacific Northwest where more than 90 percent of electrical energy is supplied by hydroelectric power sources. If vehicle battery recharge energy was derived from an electric outlet in that region, there is the potential for almost 25 percent savings in petroleum-based fuels at a 100-mile vehicle design range. Alternatively, the West-South-Central states that currently rely extensively on natural gas for fueling electric generating plants would benefit the least in saving petroleum-based fuels.

Because the hybrid heat engine/battery vehicle could be considered as an intermediate step between the conventionally powered vehicle and the all-electric vehicle (or as competitive with the all-electric vehicle), it is of interest to determine the comparable energy savings and design operating range for all-electric vehicles of equivalent performance. Again, using the conventionally powered vehicle as a reference, Figure 11-1 presents the relative energy consumption values for hybrid and all-electric vehicles of varying weights operating over the EPA Urban Driving Cycle. The design operating range shown for the all-electric vehicles is quite limited, being no better than about 60 miles. However, for applications at these low ranges, the all-electric vehicle shows remarkably improved energy savings* compared with the hybrid vehicle, particularly for petroleum-based fuels. These savings are basically due to the improved efficiency of electric generating plants in energy production, when compared with the present automotive, gasoline-fueled, internal combustion engine.

*This does not account for battery energy that would be needed by the all-electric vehicle for operating accessories (e.g., power steering, power brakes, compartment heater) which would also reduce vehicle operating range.

The poor operating range of the all-electric vehicle can be improved by relaxing the vehicle performance requirements in order to reduce the weight of the electric drive motor, thereby having more weight available for installed battery capacity. This improvement in range is illustrated in Figure 11-2a for both nickel-zinc and lead-acid battery systems in a 4000-lb car. Reductions in both acceleration and cruise speed can provide operating range over 100 miles for the nickel-zinc system. A reduction in allowable powertrain weight from 1500 to 1210 lb (see Section 7) produces the opposite effect, and large reductions in range are seen in Figure 11-2b.

The overall assessment is that hybrid heat engine/battery vehicles can provide energy savings over present, conventionally powered, vehicles while meeting exhaust emission standards. But the achievement of this capability requires compromises in vehicle design weight, design cruise speed, and design operating range. In addition, low-performance, all-electric vehicles have the potential to approach being competitive with high-performance hybrid heat engine/electric 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.

11.2

HEAT ENGINE/FLYWHEEL HYBRID VEHICLES

These systems have virtually no restriction on design operating range and have a broad potential for energy savings. For urban driving applications, a comparison with conventionally powered vehicles shows 8 to 10 percent fuel energy savings for series configurations and 15 to 18 percent for parallel configurations. Additional savings would be possible with regenerative braking. For example, the parallel configuration with this feature can save as much as 27 percent in energy consumption on the same basis of comparison.

All these savings apply basically to petroleum-based fuels because this type of hybrid system 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. (Recharging from outside sources rapidly reduces operating range to generally less than 30 miles.) Hence, there is no reliance

on electric generating stations, and there is no geographic partiality governing introduction of the vehicle into the consumer market.

Only small differences in energy savings separate different weight vehicles and different design cruise speed vehicles. However, the effects of weight and cruise speed on emissions are much greater. High design cruise speeds and low vehicle weights offer the largest emissions reductions, particularly for NO_x . For a 2500-lb series configuration car, the NO_x levels are less than 70 percent of the 1975-76 standards. Since the 6000-lb van produces emissions well in excess of the standards, it cannot be considered as a viable contender to the conventionally powered vehicle for urban driving applications. Therefore, with vehicle weight ranging up to about 4000 pounds, a full performance heat engine/flywheel hybrid vehicle can provide both energy and emissions savings for almost all urban driving requirements.

For low-speed, stop-and-go delivery service (e.g., postal delivery), this vehicle has very good potential (superior to urban driving), and in this application even the 6000-lb van is very well suited. By contrast, sustained high-speed driving is not a suitable role for the heat engine/flywheel hybrid vehicle. As in the battery system, a parallel powertrain configuration is needed to compete with the conventionally powered car in this application; for the flywheel system, only the 4000-lb car would be a suitable candidate from the standpoint of energy consumption.*

The use of a very high-speed (42,000 rpm) plastic-reinforced flywheel in place of the 24,600 rpm steel flywheel gave very poor results in terms of energy and emissions savings for a 4000-lb car. The problem lies with the large parasitic power losses of these flywheels created by aerodynamic drag, bearing drag, seal drag, and vacuum pump power requirements for maintaining low pressure in the flywheel housing. Keeping parasitic losses to a minimum will likely be the single most important design problem. Further study is needed to aid in the optimum selection of rotor housing

*As noted in Section 10, a 6000-lb car would also be expected to offer competitive energy consumption, but not the 6000-lb van because of its high drag body.

pressure and rotor size and speed for a given vehicle application. A technique for reducing parasitic losses is to design smaller, lower-speed rotors that are not loaded to maximum working stress. The resulting impact on vehicle performance would be to reduce the number of repetitive maximum accelerations available to the driver.

The assessment of hybrid heat engine/flywheel vehicles is that they are capable of significant energy savings over conventionally powered vehicles, particularly for stop-and-go driving applications. Use as a high-speed highway vehicle would be least favored. In urban driving situations they can provide major reductions in energy consumption without the design operating range restrictions associated with the hybrid heat engine/battery vehicle. However, to meet the Federal NO_x emission standard, compromises must be sought between vehicle design cruise speed and vehicle weight with a necessary trend toward higher design cruise speed combined with lower vehicle weight. The appropriate tradeoffs here, as with the hybrid heat engine/battery vehicle, 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.

11.3 OPTIONS FOR POTENTIAL ENERGY SAVINGS

It has been seen that, on the basis of total energy consumption, the more efficient heat engine/flywheel system uses less 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 a near-term option. 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.

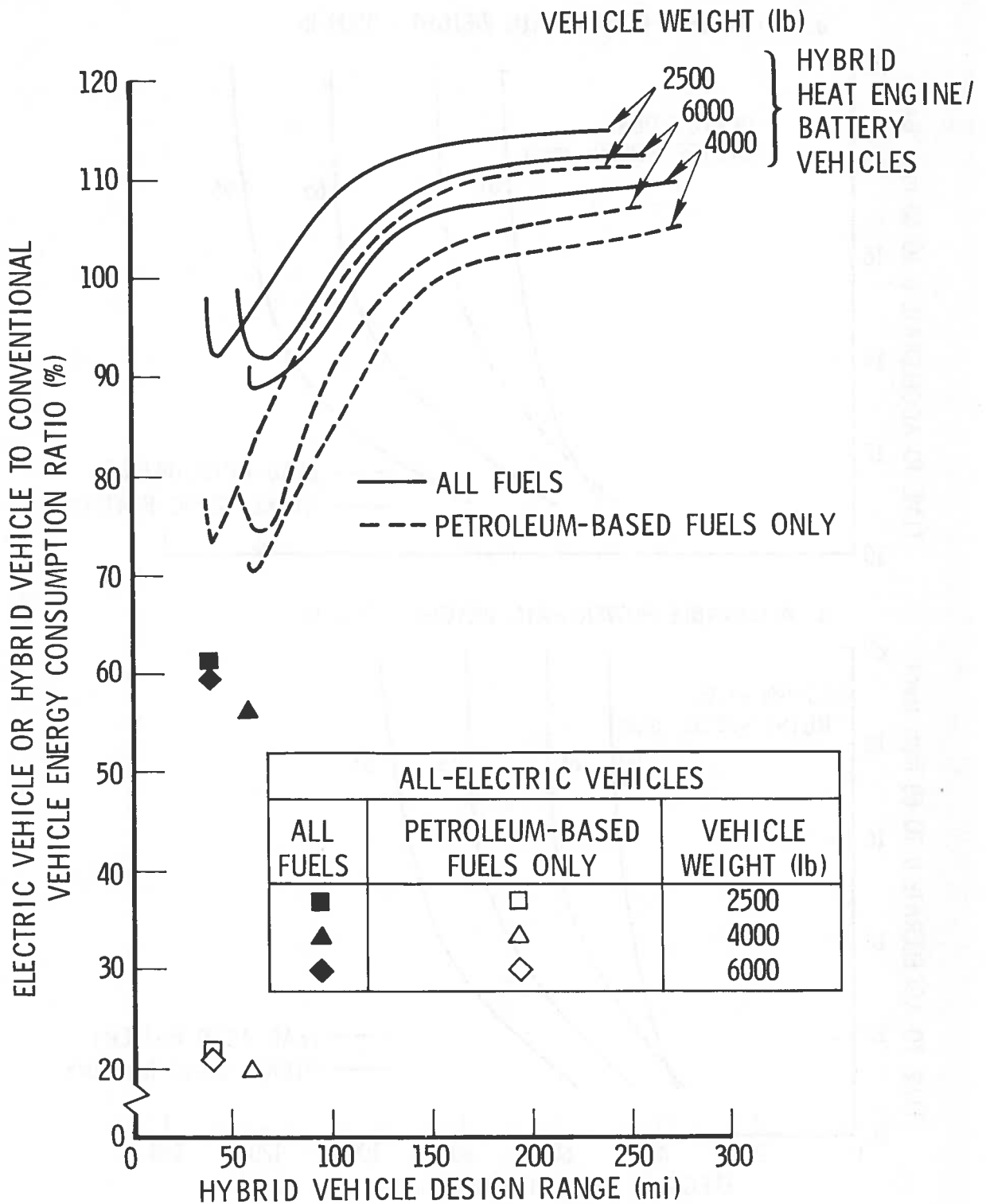


FIGURE 11-1. ENERGY CONSUMPTION COMPARISON FOR TWO TYPES OF VEHICLES: EPA URBAN DRIVING CYCLE, VEHICLE DESIGN PEAK CRUISE SPEED = 65 MPH, SERIES CONFIGURATION

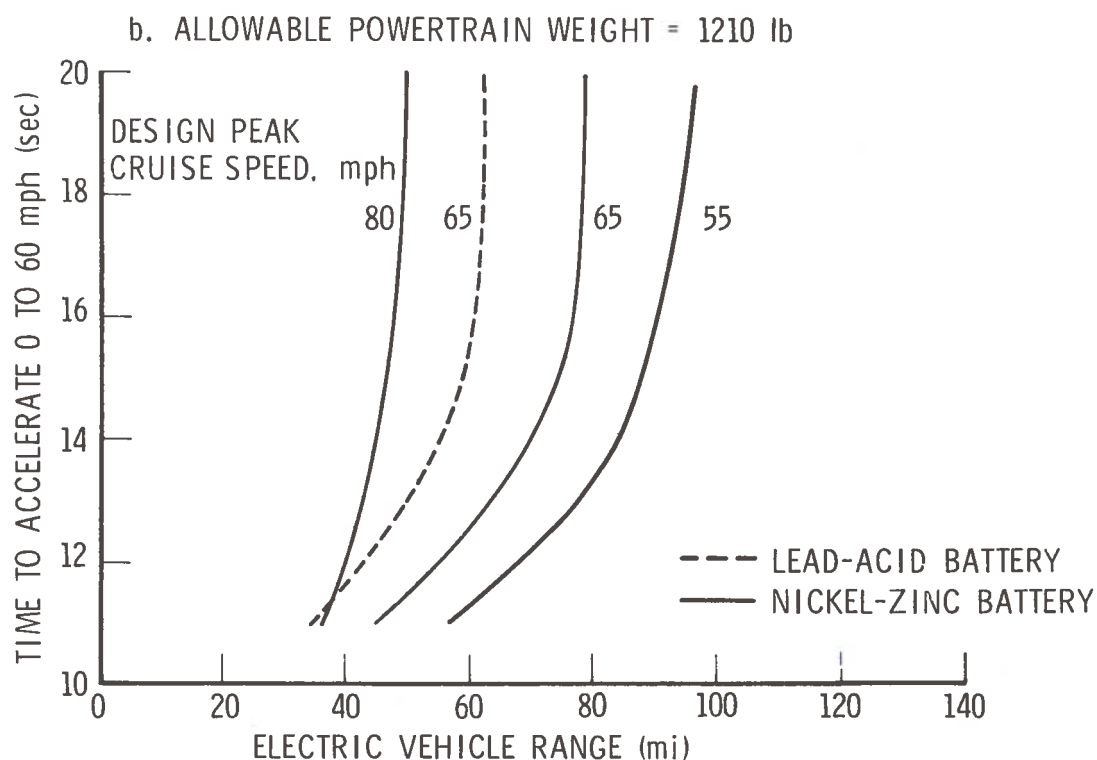
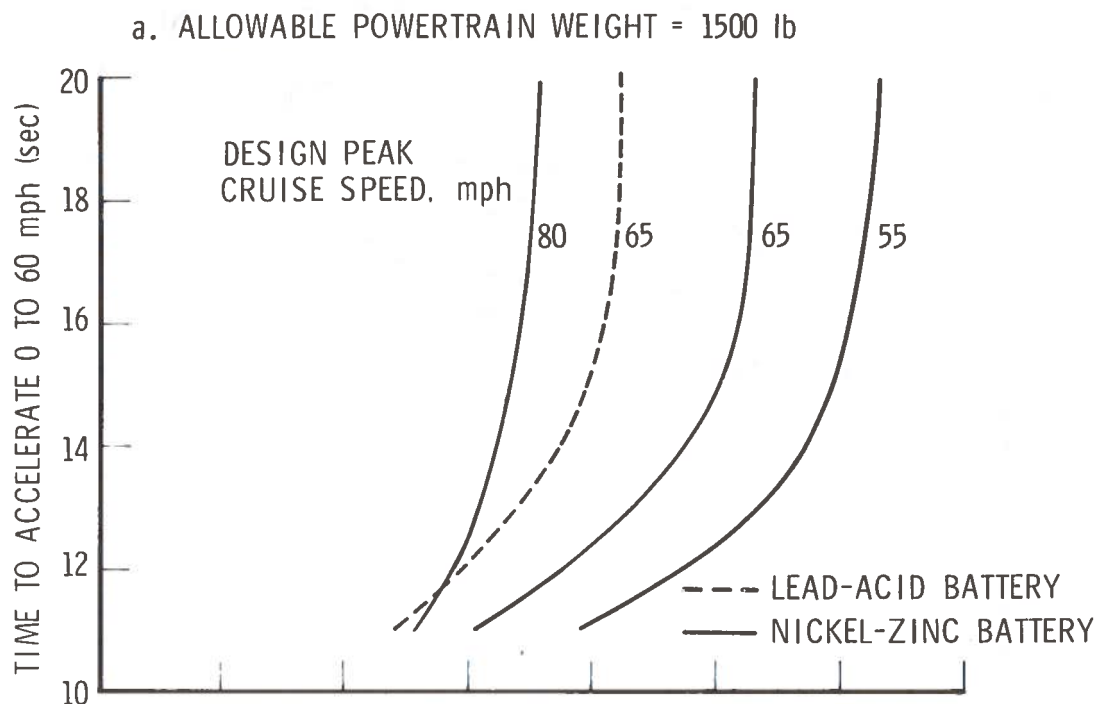


FIGURE 11-2. EFFECT OF DESIGN PEAK ACCELERATION AND DESIGN PEAK CRUISE SPEED ON ELECTRIC VEHICLE OPERATING RANGE: EPA URBAN DRIVING CYCLE, VEHICLE WEIGHT = 4000 LB

APPENDIX

REPORT OF INVENTIONS

This work resulted in no new discoveries or inventions although there were improvements in the data base on the operating characteristics of the various drive train components that would be used for different hybrid vehicle applications. These characteristics were then used in a computer simulation to establish a data base for fuel consumption and exhaust emissions for different size vehicles traversing different driving cycles.

