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**Urban Mass
Transportation
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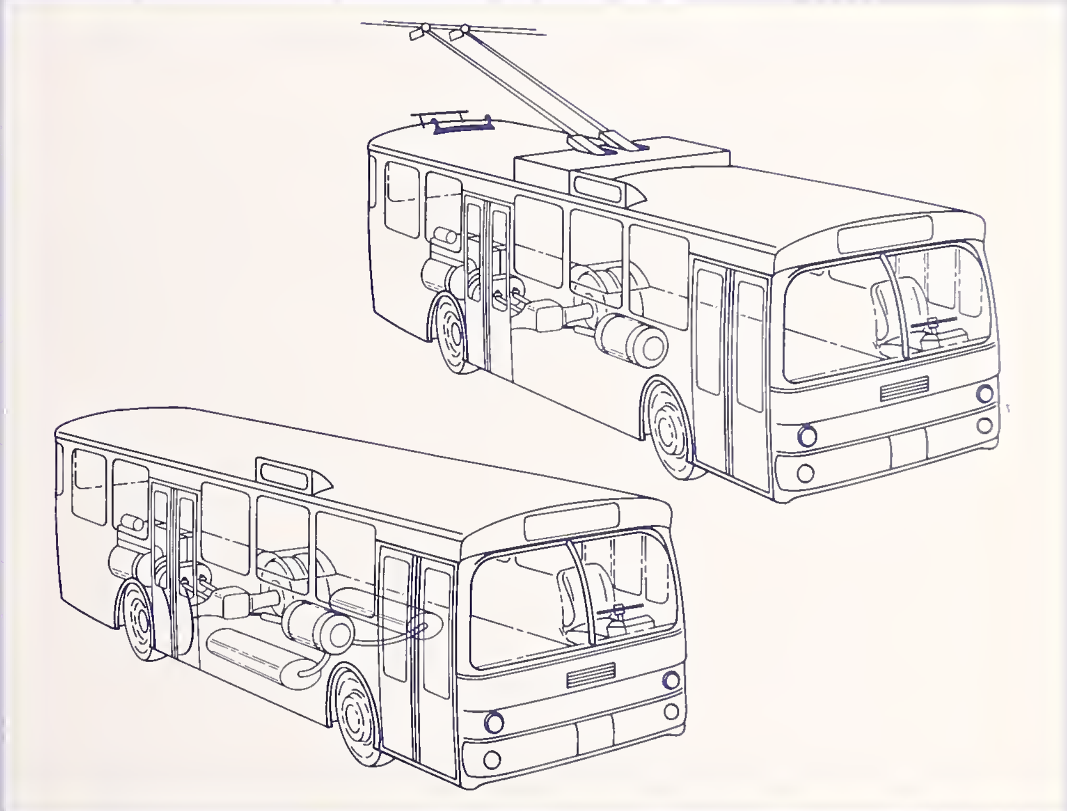
Hybrid Propulsion Technologies for Urban Bus Transit

Prepared by:
Transportation Systems Center

Final Report
November 1984



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16. Abstract

This report presents overview information on hybrid propulsion technologies (also called "dual" propulsion) in order to increase the transit community's awareness and understanding of bus propulsion designs that offer extended use capability for trolley-emergency, short-range, and back-up propulsion for trolley buses or offer some overall energy or fuel savings. Technical material is provided to a greater extent on systems that are novel or appear to offer the greatest potential for future commercial development. This information is provided to make the transit community aware of advancements in hybrid technology that could help them better utilize their existing equipment or help them in decisions regarding the procurement of new vehicles.

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PREFACE

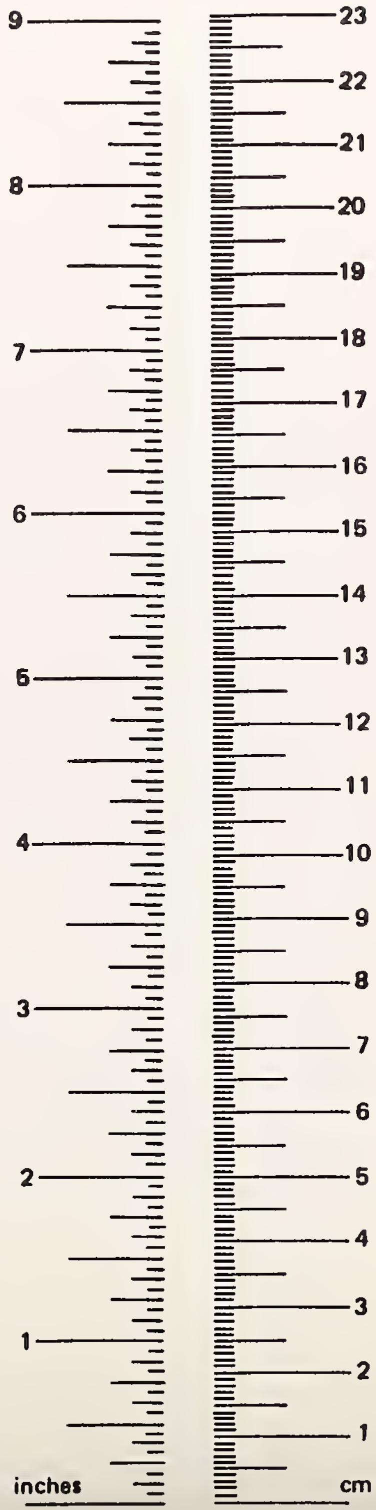
This report presents overview information on hybrid propulsion technologies (also called "dual" propulsion). The Urban Mass Transportation Administration (UMTA) Office of Technical Assistance sponsored this work in order to increase the transit community's awareness and understanding of bus propulsion designs that offer extended use capability for trolley-emergency, short-range, and back-up propulsion for trolley buses or offer some overall fuel or energy savings.

This report was prepared by the Office of Systems Assessment of the Transportation Systems Center, with support from Mr. Ted Hawkes of the Transportation Equipment Development Company and Mr. John Aurelius of the New Jersey Transit Corporation.

METRIC CONVERSION FACTORS

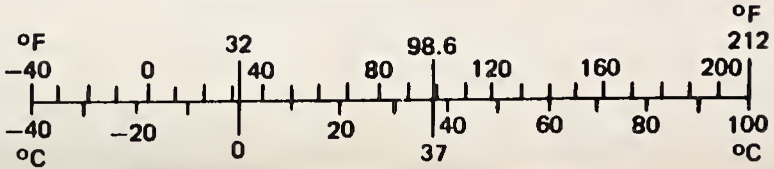
Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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

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EXECUTIVE SUMMARY

In the past decade, there has been increased interest in transit bus designs offering a second, on-board means of powering the vehicle. To date, the interest has been strongest in trolley bus systems where auxiliary power sources have been used for limited, off-wire operations. In addition, in order to improve the fuel economy of diesel coaches, equipment suppliers have developed auxiliary propulsion equipment which reclaims energy normally lost in braking for reuse during vehicle acceleration. At this time there is a significant amount of propulsion technology that could be demonstrated and evaluated by transit authorities to improve bus and trolley operations. The purpose of this report is to stimulate interest in hybrid propulsion systems for application to domestic transit where potential benefits appear to warrant test and demonstration. It does not include information on operational experience or evaluations of systems in actual transit service. Technical material is provided to a greater extent on systems that are novel or appear to offer the greatest potential for future commercial development. This information is provided to make the transit community aware of advancements in hybrid technology that could help them better utilize their existing equipment or help them in decisions regarding the procurement of new vehicles.

A useful categorization of this equipment, commonly grouped under the title of hybrid propulsion systems, is as follows:

- Dual hybrid - both propulsion systems capable of approximately equal performance.
- Auxiliary hybrid - the secondary or back-up propulsion system has limited capability for such purposes as emergency movement of trolley coaches, for off-wire mobility or movement of diesel buses through air quality or noise-sensitive areas.
- Auxiliary power for load leveling - the secondary power source, such as a regenerative, mechanical energy storage device, is used as prime or supplementary power only during the acceleration phase of the bus operating profile.

A significant portion of the hybrid propulsion or energy equipment research conducted worldwide has focused on trolley bus applications. Much of the hybrid propulsion research has been conducted in Europe. Major foreign contributors to the development of this technology include Mercedes and M.A.N. in Germany, Renault in France, Fiat in Italy, and Volvo in Sweden. The Urban Mass Transportation Administration (UMTA) has sponsored hybrid propulsion studies and demonstrations in this country in diesel-powered or battery auxiliary systems for trolley buses in Boston, Dayton and San Francisco; stored hydraulic energy systems in Portland, Oregon; inductive coupling research in Santa Barbara, California; and dual-powered (electric/diesel) trolley buses in Seattle, Washington. However, outside of these UMTA-funded projects, little activity has occurred in the U.S. transit community on hybrid propulsion systems. The accompanying table, entitled "Summary of Hybrid Propulsion Technology - Worldwide," provides a useful reference to the general characteristics of a variety of hybrid systems.

Information on hybrid technology is difficult to obtain due to proprietary status claimed by manufacturers. In certain cases, the information that is available is either theoretical or laboratory data, or is too limited in quantity to allow useful conclusions to be drawn. Often, there is no clear distinction between test data and revenue service data nor between experimental and production vehicles.

It is clear that more information is needed concerning cost and performance of vehicles using these hybrid propulsion systems and revenue service conditions so that judgments can be made of the cost-effectiveness of this technology in various applications.

1. INTRODUCTION

1.1 GENERAL

Hybrid propulsion systems for urban transit buses, as the words imply, incorporate two power sources for moving the vehicle. With the development and evolution of various propulsion systems, the number of possible combinations for application to transit coaches has grown. Generally, hybrid systems encompass one of the following combinations of technology:

a. Two separate propulsion systems (e.g., diesel engine/transmission, or electric motor) each with independent drivelines; or

b. Two energy sources (e.g., battery, flywheel) where part or all of the driveline is shared by each energy source. This latter category becomes a "catch-all" because of variety of designs, and combinations and functions of individual energy sources.

There are a number of potential power sources, many of which have been or are being developed both in this country and abroad, that are suitable candidates for combination in a hybrid design. Hybrid propulsion concepts combine two energy sources and/or propulsion systems each having a demonstrated advantage for part of the transit bus operating cycle.

It is important to note that the concept of hybrid propulsion* is not new nor is it foreign to U.S. transit applications. As early as the 1930s, a sizable fleet of trolley buses (600), capable of operating from overhead

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*Hybrid propulsion systems should be distinguished from "dual mode." The concept of hybrid propulsion primarily addresses the "engine" or power source of the vehicle. Dual mode, on the other hand, suggests either alternate methods of movement, such as rail and rubber tire or bus and guideway combinations, or alternate control modes, such as automatic and manual.

wires or from gasoline engines, were used in transit operation in New Jersey. Figure 1 is a photograph of the thirty-five-foot Yellow Coach having such a hybrid system. Although some early examples do exist, the research, development and testing of a wide range of concepts for hybrid propulsion really did not emerge until the 1970s.

To date, most hybrid propulsion research and development has been done in Europe and has generally focused on trolley bus applications. More recently, there has been a growing interest, again primarily in Europe, in the development of hybrid propulsion technologies for diesel bus applications that will recover and store the kinetic energy normally dissipated as heat during braking, and reuse it later for reaccelerating the vehicle.

Hybrid propulsion can provide the best features of several propulsion systems in one system while minimizing the effects of their less attractive features. For example, the trolley bus has numerous advantages, such as minimal air pollutants and noise emissions as well as adequate power in small volume for heavy loads and steep grades. However, the route coverage is limited by the availability of overhead wires. In addition, vehicle electrical breakdowns or unanticipated blockages of the route can cause serious service problems. Certain hybrid propulsion designs could, on the other hand, permit route extension and route flexibility without attendant extension of the electrical distribution system. Such designs might also permit detour of the vehicle around road blockages or permit movement in spite of electrical failures.

From a similar perspective, diesel propulsion systems have been the mainstay of U.S. urban bus operations for a number of decades with a demonstrated history of high reliability and good performance. However, because of increasing concern for rising fuel prices, hybrid concepts have been developed to recover and store energy normally lost in deceleration for later use in powering the bus during acceleration, thus effectively increasing fuel efficiencies.

There are three categories of hybrid propulsion systems designed for use in transit coaches - dual power, auxiliary power and load-leveling

FIGURE 1. THIRTY-FIVE-FOOT HYBRID YELLOW COACH

systems. Hybrid propulsion technologies are available for deployment and evaluation by domestic, public transit agencies, both for demonstration and for revenue service operation. Numerous cooperative research efforts between industry and government in Germany, Sweden, Finland and Denmark have resulted in prototype developments and even commercial production in some instances. Several transit agencies in this country (Seattle, Boston, Santa Barbara, Dayton, Portland, San Francisco) are actively investigating, testing and evaluating hybrid propulsion technology. In addition, there are still numerous other propulsion concepts with potential advantages which remain to be tested.

1.2 PURPOSE

This study was conducted to provide technical information to public transit and state DOT managers and planners concerning hybrid propulsion technology for transit buses. It is hoped that this report will stimulate further interest in hybrid propulsion systems among transit agencies and equipment supply industries as well as encourage demonstrations and evaluations of innovative propulsion concepts in this country to assess the operational advantages of this new technology.

1.3 REPORT CONTENT AND SCOPE

This report describes the technical aspects of the development of hybrid propulsion systems. It does not include information on operational experience or evaluations of the concepts in actual transit service. Introductory technical information is provided on those designs that currently appear to offer the best potential for commercial development and eventual deployment in U.S. public transit. Following a brief discussion of the individual power or propulsion units that could be used for transit bus applications, the report concentrates on specific hybrid configurations which are in the commercial development stage or in actual operation.

To a large extent, the sources of information for this report were reports from equipment and bus manufacturers. Such information is not usually detailed enough for comparisons among alternatives and often contains more theory than actual performance data, particularly where the design or development is in the concept or prototype development stages. Consequently, this report will not be a technology primer but an overview of current activities and preview of coming events in hybrid propulsion technology for urban buses.

2. PROPULSION OPTIONS

2.1 GENERAL

Primary propulsion systems for transit buses include several kinds of combustion engines, as well as electric motors using utility power, batteries, and in the future possibly the fuel cell. Power can be handled on buses in mechanical, electrical or hydraulic form. Energy recovered from braking can be stored on-board or transmitted for use by other vehicles via an electrification system.

Figure 2 shows six types of engines, a fuel cell, and two ways to use utility power-electrification and energy storage (battery) with intermittent charging. In addition, four ways of transferring power to and from the wheels are shown, and several methods of conditioning and control are indicated. This simplified schematic is provided to illustrate that single drives and hybrids can be built up from these components by selecting appropriate combinations of components and tying them together. The appropriateness of combinations of propulsion mechanisms depends on a number of factors, including costs, energy (fuel) availability, extent of development of the technology, safety considerations and performance requirements for service. Of these factors only the performance requirements may need further definition.

Power systems used for auxiliary, back-up vehicle propulsion generally have low top-speed, acceleration and grade-climbing performance requirements. On the other hand, systems used to substitute for the primary system or to augment the primary system have more stringent performance requirements. A representative power profile for transit buses, shown in Figure 3, graphically illustrates the demands placed on the propulsion system in a standard coach during routine service, particularly the high energy requirement needed to accelerate a transit coach. This requirement translates into a design where the secondary power system should have sufficient independent peak power, or a design where energy recovered during braking can be applied to assist the vehicle acceleration.

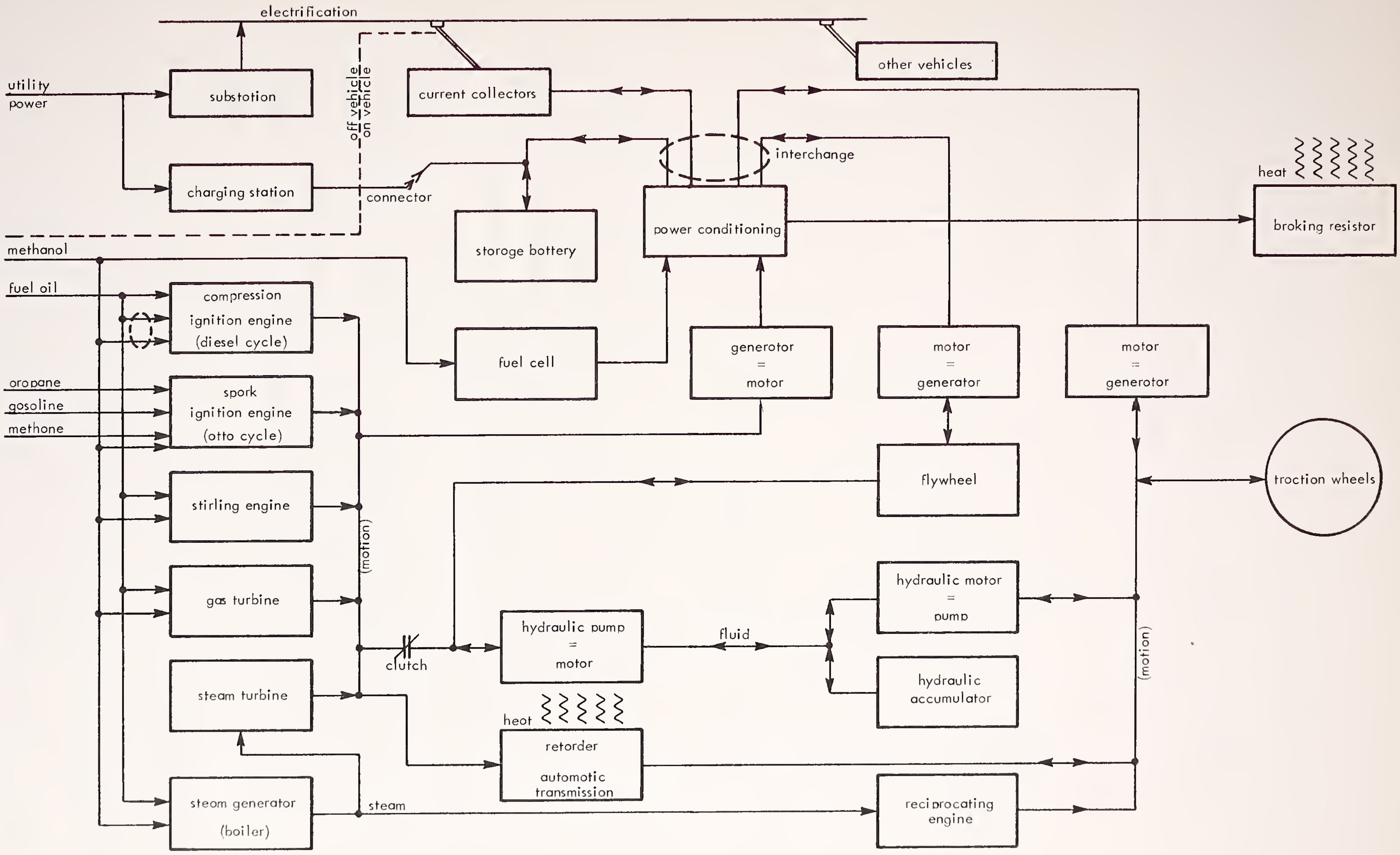

FIGURE 2. SCHEMATIC OF POSSIBLE HYBRID CONFIGURATIONS

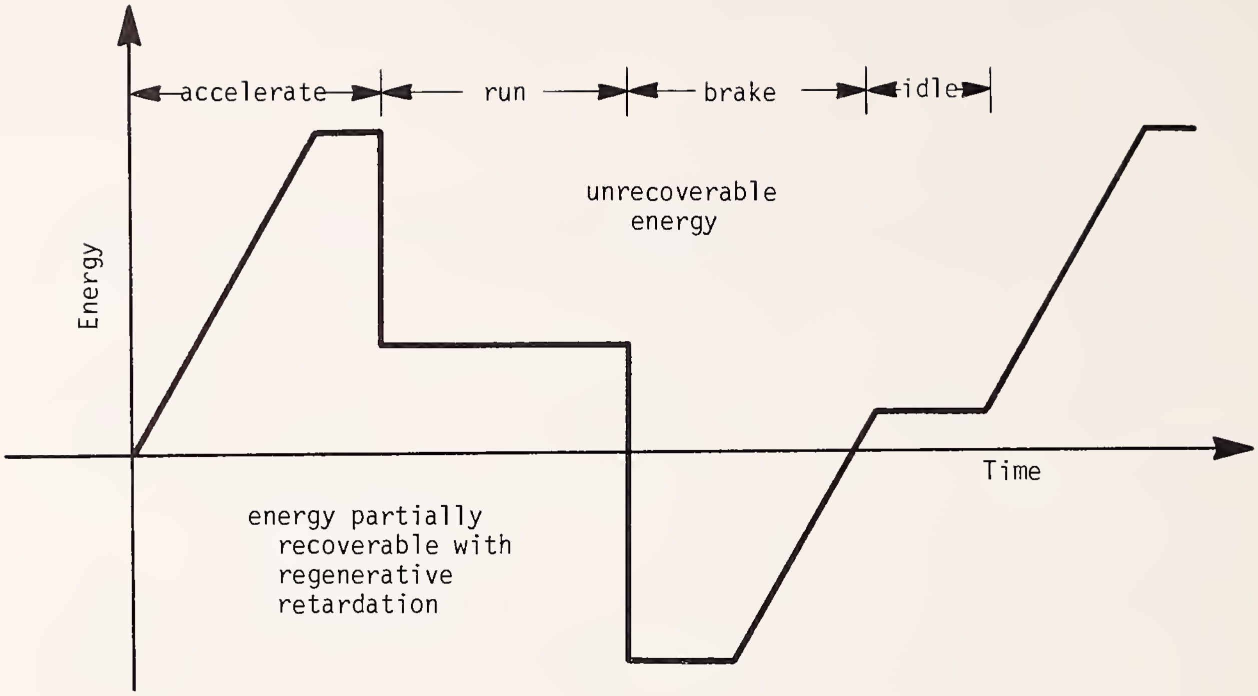

FIGURE 3. TYPICAL TRANSIT VEHICLE POWER PROFILE

Braking systems dissipate large amounts of energy in providing rapid, safe deceleration for transit coaches. It is possible to convert and store some of this energy for use later in acceleration. This concept is often referred to as "load-leveling". It is the basis of many hybrid propulsion concepts, specifically those concepts using flywheel or hydraulic accumulator technology.

The following paragraphs provide information on thermal, electric and mechanical propulsion systems that have application to transit bus service. More details are provided on the more innovative propulsion systems, such as batteries, fuel cell, and mechanical energy storage systems.

2.2 THERMAL ENGINES

Diesel Engine

The diesel or compression-ignition engine is quite efficient over a good range of speeds and power output levels. In slow, city service a 40-foot diesel bus should deliver about 3-5 miles per gallon. Commuter or express routes fuel mileage may increase to more than 5 miles per gallon. The diesel engine in the 6 or 8 cylinder configuration has become the workhorse of the transit industry. In U.S. urban public transit, the number of diesel engine coaches exceeds fifty thousand. This number is augmented by thousands more in the intercity and charter industry.

Gasoline Engine

The spark-ignition internal combustion engine is most commonly operated with gasoline, but it can use a variety of fuels that either are normally gases or that can be easily vaporized. It uses more fuel and requires more maintenance than the diesel, and today is rarely used for heavy-duty vehicles, such as large transit coaches. It is used extensively, however, for smaller vehicles such as mini buses or vans. It is lighter and cheaper to construct than a comparable diesel and it generates less noise and vibration.

Gas Turbine

The gas turbine engine can produce high power in a small, lightweight unit. Since it is not a reciprocating engine, there is little vibration. Its efficiency is high when fully loaded at optimum rpm, but at lower outputs the fuel demands do not decrease accordingly. Gas turbines have been used in experimental buses and trucks, and Amtrak has a small fleet of turbine-powered trains. All these vehicles consume significantly more fuel than they would if they were diesel-powered, although cost as well as quantity should be considered. Gas turbine development is concentrating on greater efficiency, and on operation with non-petroleum fuels.

Stirling Engine

Low emissions and quiet operation are attributed to the Stirling engine, an external combustion engine using a gas as the working fluid in a closed cycle. It presents problems of internal sealing and heat exchange, and no heavy duty transit vehicle applications to date are known.

Steam Engines

The two basic types of steam engines are the reciprocating engine and the steam turbine. The reciprocating steam engine was the first practical vehicle engine and it was the basic power plant in the railroad industry for nearly a century. Steam was also a contender against gasoline engines in the early days of the automobile industry. Since, in the steam generator, combustion takes place as a continuous process and not under compression, polluting emissions are usually low. The reciprocating steam engine operates quietly and can be connected directly to the wheels because it requires no transmission. A research project was conducted in California with steam-powered buses in the early 1970s. The prototype buses were satisfactory in many ways, with low polluting emissions, but they used considerably more fuel than their diesel-powered counterparts. The high fuel consumption, acceptable at 1970 prices, became unacceptable when fuel prices jumped in the middle of the decade.

2.3 ELECTRIC MOTOR PROPULSION SYSTEMS

Electric motors have been used to power transit vehicles for many years. The source of the electrical power is principally the electric utilities, although batteries have also been used to a lesser extent. The fuel cell is beginning to emerge as an energy source, as is the inductive coupling concept; both deserve further investigation as sources of electrical power.

2.3.1 Utility Power

The principal electric bus today is the trolley bus, which uses utility power delivered via an electrical distribution system which is continuous the whole length of the routes. Virtually all trolley buses use direct current at 600 to 700 volts (Lugano, Switzerland, uses 1000 volts). The principal objection to the trolley bus relates to its infrastructure. The cost and visual impact of the catenary, its supporting poles, suspension system, hardware, insulators, substations, safety devices, etc., dictate the route structure and range.

Today's trolley buses use choppers to convert the dc to ac, thus enabling better and easier control of traction motors, with reduced energy consumption and maintenance. Chopper control also makes regenerative braking practical since the braking energy can be fed back into the distribution system. Regenerative braking also reduces mechanical brake usage and extends the life of brake linings.

2.3.2 Battery Power

Batteries* have been used with limited success to power transit vehicles. This is primarily due to the characteristics of the chemical process of batteries. The stored energy (energy density in watt-hours per pound) in the battery is limited by the amount of reactant on the electrodes. In addition to the quantity of reactant, the chemical process is dependent on the physical composition of electrodes, the internal, electrical resistance and the temperature of the battery. Commercially available batteries have a usable energy density of only about 15 watt-hours per pound (33 Wh/kg). An electric bus uses perhaps 300 kilowatt-hours of energy in a day. A currently available battery system to store this much energy would weigh at least 10 tons.

The lead-acid battery has been the most commonly used battery in the industry, due principally to its low cost and ready availability. Compared to other types, it has a high cell voltage, relatively good energy density and reasonably long life. Very high discharge rates can be used for short periods (i.e., cranking). At the end of its life, the lead battery is easily recyclable. Heavy-duty lead acid batteries for traction use have a life of about 2500 charge/discharge cycles, or five operational years (at a rate of two cycles per weekday - approximately that required by common urban transit service). However, the battery degrades with use

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*A useful technical reference is: "Assessment of Research Needs for Advanced Battery Systems," NMAB-390 National Material Advisory Board Commission on Engineering and Technical Systems, National Research Council, PB 82-227349.

and age, and will only store about two-thirds its initial rated capacity near the end of its life cycle. To achieve the longest possible service life, a lead-acid battery should not be discharged to less than 50 percent of capacity, or recharged at a fast rate.

Table 1 provides information on characteristics and status of various production and developmental battery systems suitable for application to electric transit coaches.

2.3.3 On-Board Generation of Power--Fuel Cell

The fuel cell makes electricity directly from a fuel such as methanol without combustion and without moving parts. It is over 50 percent efficient, twice as good as a diesel engine. Fuel cells are routinely used for space applications, and trial quantities have been manufactured for military use on land. Larger units are being developed for electric utilities. The fuel cell system can be likened to a power station. When incorporated as part of the transit vehicle propulsion system it becomes a power station on wheels, one which takes the stored on-board fuel and processes it into electrical energy to meet requirements of vehicle propulsion. To provide this controlled energy source, the fuel cell system is divided into four subsystems:

a. The fuel processor which, through a reformer or other process, generates and prepares the fuel;

b. The fuel cell which generates the electrical energy;

c. The power conditioner which transforms the electrical energy into a form required by the propulsion motors;

d. The fuel cell controller which regulates and manages the fuel cell system during operation, including start-up, shut-down, throttle commands and emergency situations.

TABLE 1. SUMMARY OF BATTERY CHARACTERISTICS

		Theoretical		Demonstrated			Projected			
CELL TYPE	VOLTS/ CELL VOLTS	ENERGY DENSITY WH/Kg	POWER DENSITY W/Kg	ENERGY DENSITY WH/Kg	CYCLE LIFE # of CYC	POWER DENSITY WH/Kg	ENERGY DENSITY WH/Kg	CYCLE LIFE # of CYC	POWER DENSITY WH/Kg	REMARKS (AS APPLICABLE TO ELECTRIC VEHICLE (EV) USE.)
Lead Acid $Ph/H_2SO_4/Pb$	2.1	175	30-40	50-100	400 +	50	150	1000	\$60	1. Used for EV short driving cycles less than 50 miles. 2. Batteries for EV showed poor user experience to predicted laboratory-estimated performance. 3. Higher energy density requires thinner electrode designs - however this results in poorer cycle life.
Nickel Iron Fe/KOH/NiOOH	1.4	267	40-50	50-100	300-600	65	175	2000	\$60	1. Used for EV driving cycles less than 75 miles. 2. If production versions of this battery live up to laboratory performance, the nickel-iron cell could replace the lead-acid cell for EV operation. 3. The major impediments to the use of the nickel-iron cell are cost and availability.
Nickel Zinc Zn/KOH/NiOOH	1.7	326	60-75	100-150	100-300	90	200	1000	\$65	1. Used for EV driving cycles less than 100 miles. 2. Failure to live up to predicted laboratory performance objectives. 3. Battery life has been plagued by failure to find a solution to the formation of Zn dendrites on the Zn electrode. When these form, the dendrites penetrate the separators and short the cell.
Nickel Cadmium Cd/KOH/NiOOH	1.3	210	300	19-34	300-2000	>7300	35	>2000	\$900	1. The limited world supply of cadmium makes the nickel-cadmium battery less attractive as an energy source for EVs.
Nickel/Hydrogen H_2/KOH/NiOOH	1.3	443	45-50	200-250	6000 +	70	200	10000 +	\$100/200	1. Has energy density suitable for EVs. 2. Expected life exceeds that of EV. 3. The dominant concern is safety. Hydrogen must be stored under pressure.
Zinc/Zinc Bromide/Bromine Zn/Br_2	1.828	430	81	65	100	125	75	500	\$25/30	1. Requires abundant and inexpensive material, simple construction for flow batteries. However, it is difficult to identify economical materials which are stable in a bromide environment. 2. Zn dendrites form on the Zn electrode. 3. Bromide vapors and solutions are toxic and highly corrosive. 4. Extensive design engineering and safety tests required to prove acceptability for EV use.

The fuel cell conversion process is significantly improved when heat is added to the process. Under increased temperature, the mass transfer of fuel is enhanced, the reaction rate at the electrodes is increased, the cell resistance is decreased and the fuel cell is less susceptible to carbon monoxide (CO) poisoning.

Figure 5 illustrates the voltage/amperage characteristics of a representative fuel cell. There are three losses that affect the output voltage of the cell under load:

a. Ohmic losses - resistance to the flow of electrons to the external circuit and the conduction of positive ions through the electrolyte;

b. Activation losses - energy barrier inherent in the chemical reaction of the fuel cell; and

c. Concentration losses - the most serious loss occurring when the electrode reactant is hindered by the transport of the fuel mass through the electrode. Under conditions of high concentration of reactant the fuel cell voltage can drop to zero.

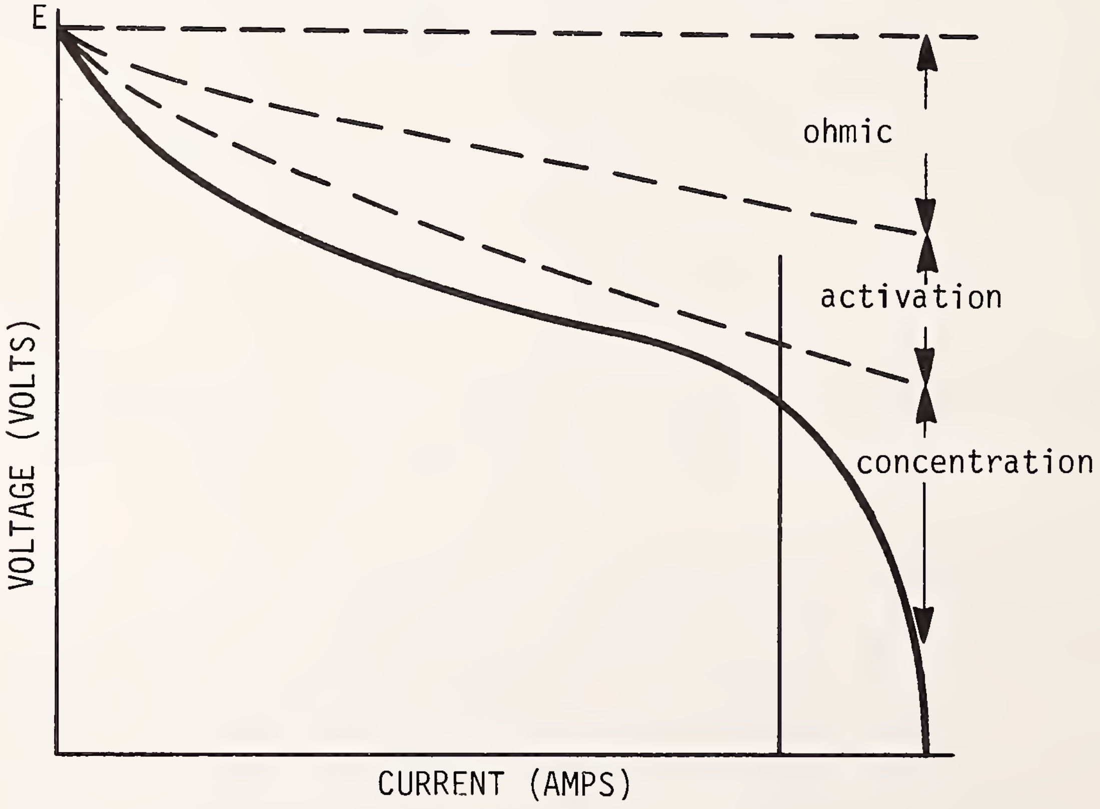

FIGURE 4. VOLTAGE/AMPERAGE CHARACTERISTICS OF REPRESENTATIVE FUEL CELL

It is generally agreed that to employ such a power source for transit vehicle propulsion requires design with over-capacity power augmentation from some auxiliary source, or possibly the use of an alternating current motor. To date, little work has been done to assess the adaptation of fuel cell technology to transit coaches. *

2.3.4 Inductive Coupling

The magnetic inductive coupling principle has been used to transfer energy from the roadway to a battery-powered vehicle. This concept has been used to recharge batteries in airport baggage cars. More recently, this principle has been investigated for application to mass transit under an UMTA research grant in cooperation with CALTRANS and the Santa Barbara Metropolitan Transit District.

Inductive coupling designs can be distinguished from a conventional transformer in that the primary and secondary windings are on separate cores. This provides an air gap between the two windings. The primary winding (the source conductors) is mounted in a laminated steel core which is embedded in the roadway (See Figure 5). The source conductors are laid parallel to the direction of the road bed and are energized by a 180 Hz as power source, which provides a constant current to the primary winding. To maximize the power transfer to the primary winding, the power factor is corrected by utilizing an adjustable capacitator bank.

The secondary winding, identified as the power pickup winding, is mounted in the transit vehicle. There are no mechanical connections between the secondary winding in the vehicle and the primary winding in the roadway. In the initial investigation in Santa Barbara, the air gap between the primary and secondary winding could vary from 0.5 to 2 inches. Such an air gap between the primary and secondary winding implies that the magnetic coupling (the mutual inductance) is not identical in both windings. The magnetic reluctance, the resistance to the flow of magnetic

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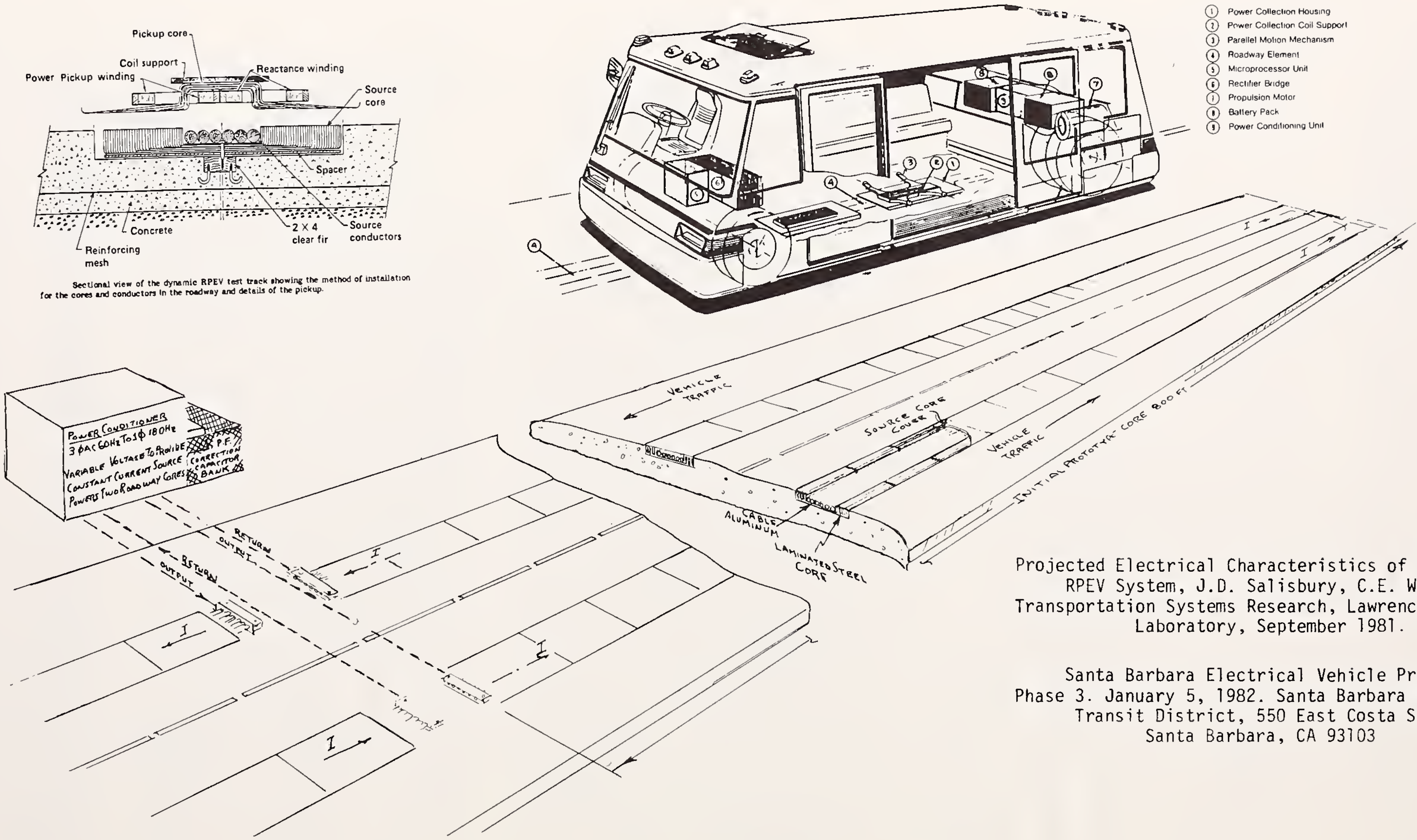
* UMTA-sponsored studies are underway: Aerospace Corp. is developing an issue paper on fuel cells for bus transit; Los Alamos National Lab. will soon begin a broader feasibility study.



Sectional view of the dynamic RPEV test track showing the method of installation for the cores and conductors in the roadway and details of the pickup.

Projected Electrical Characteristics of the Dynamic
RPEV System, J.D. Salisbury, C.E. Walter.
Transportation Systems Research, Lawrence Livermore
Laboratory, September 1981.

Santa Barbara Electrical Vehicle Project
Phase 3. January 5, 1982. Santa Barbara Metropolitan
Transit District, 550 East Costa Street
Santa Barbara, CA 93103

FIGURE 5. ROADWAY INDUCTIVE COUPLING POWER TRANSFER SYSTEM

flux, which is near zero for a complete iron path in a conventional transformer, has a high, finite value for this roadway energy transfer system. To improve the magnetic coupling and reduce the reluctance added by the air gap, the physical design generally has a large area for the transfer of flux between the two windings, employs the best magnetic core materials, and uses a method to automatically center the transit vehicle laterally/directionally over the primary winding.

It has been estimated that the power pickup would provide an average of about 10 kW/meter. For the existing Santa Barbara bus configuration three power pickup units would be required to be mounted on each bus. The buses are rated in excess of 40 kW.

Special electrical circuitry is used to "tune" the secondary winding. When the secondary is tuned, the equivalent circuit of the secondary appears to be in series with the primary, creating the same current flow in both the primary and secondary winding. In effect, this maximizes the efficiency of the energy transfer. Appropriate tuning of the secondary winding remains crucial to the technical feasibility of this concept.

2.4 MECHANICAL ENERGY STORAGE PROPULSION SYSTEMS

Mechanical energy storage devices can be used to store energy and later make it available for propulsion purposes. Typically, in transit coach applications, the energy is recovered from the vehicle braking process. In other concepts, the mechanical storage device is periodically charged at designated locations along the route. There are essentially only two mechanical energy storage systems having the energy density capabilities for transit vehicle operation: the flywheel and the hydraulic accumulator. The latter device could technically be defined as a hydraulic device rather than mechanical but for purposes of discussion it is grouped in this category. Figure 6 illustrates the foreign and domestic involvement in the development of mechanical energy storage systems.

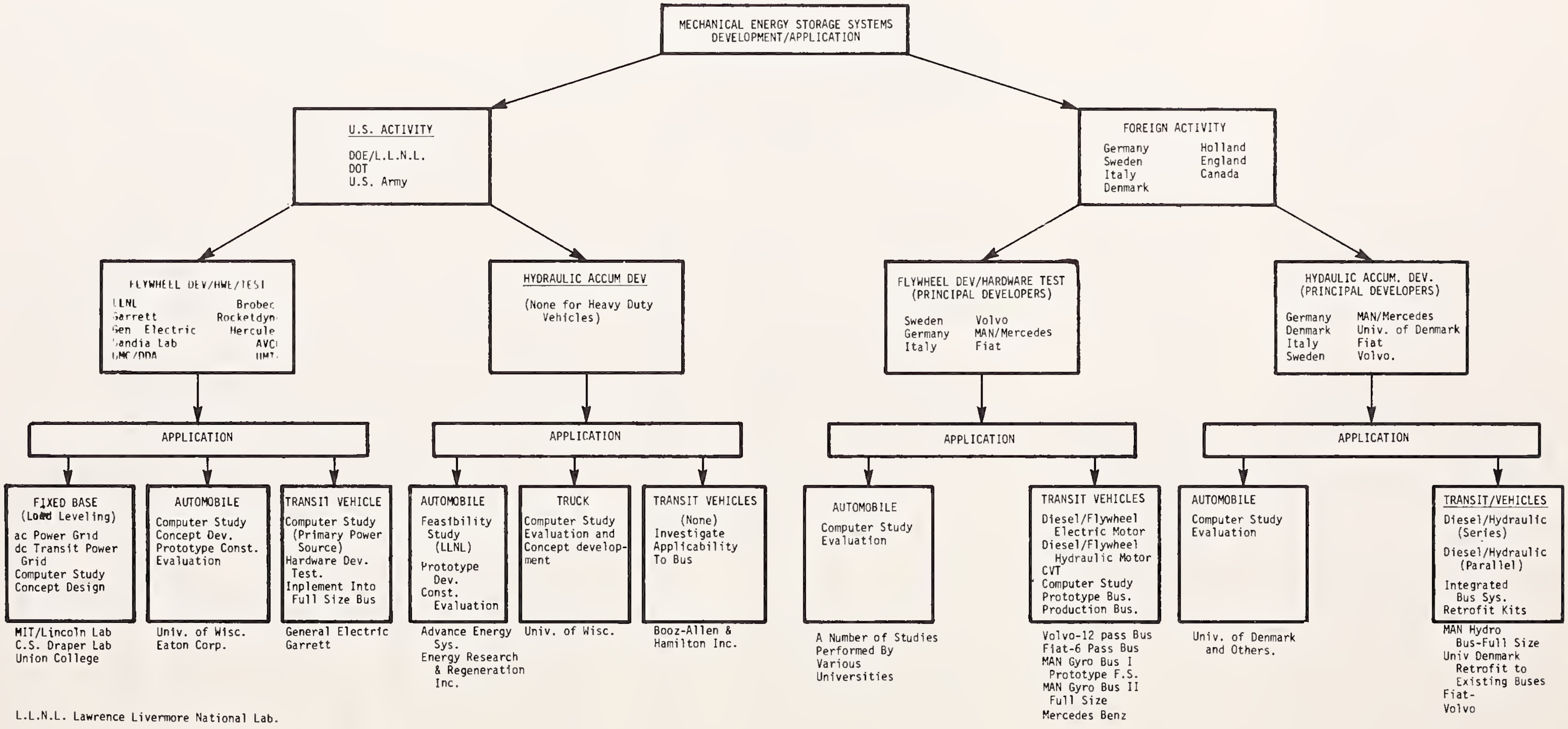


FIGURE 6. SUMMARY OF MECHANICAL ENERGY STORAGE SYSTEM DEVELOPERS AND THEIR AREAS OF INVOLVEMENT

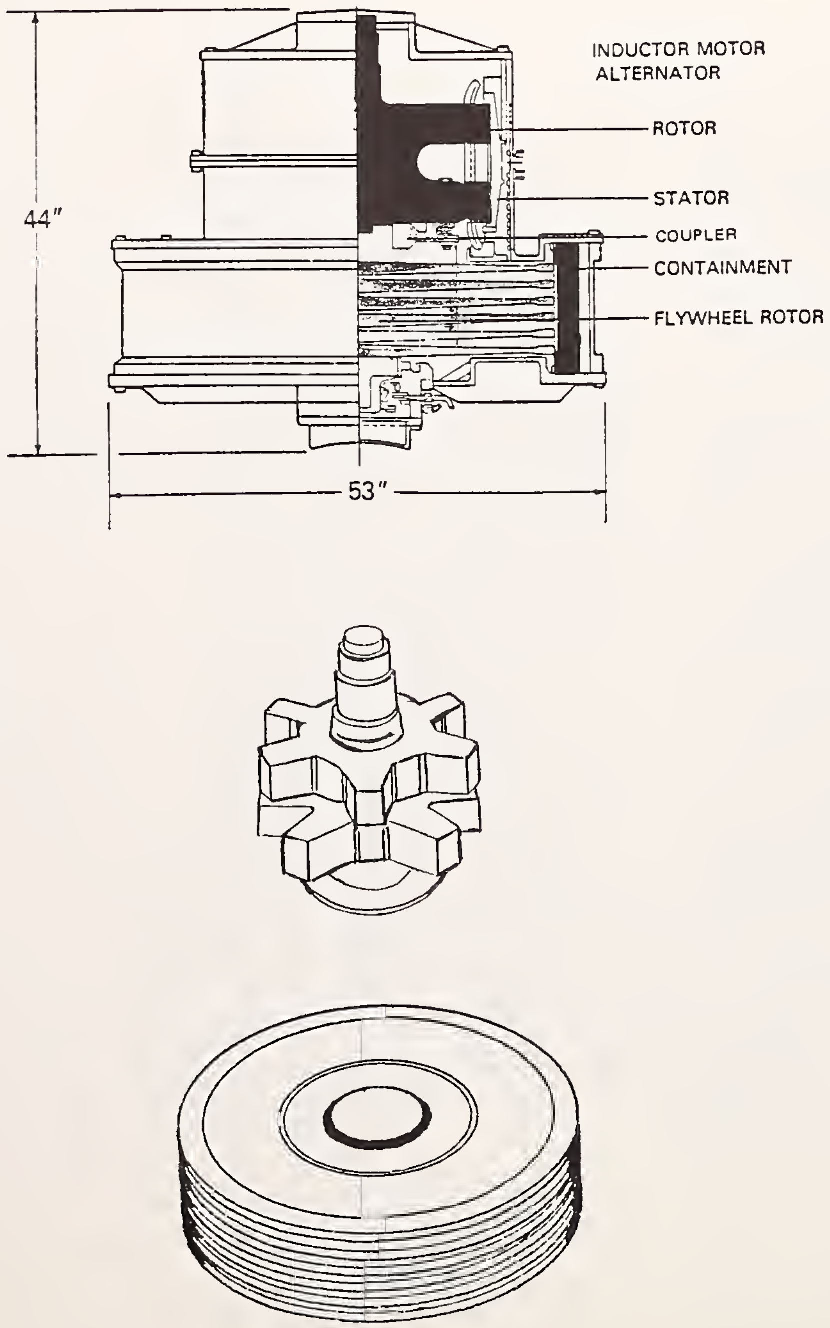
2.4.1 Flywheel

The primary property of a flywheel is its ability to store large amounts of energy by virtue of its mass, velocity and radial size. Modern technology has made it possible to design flywheels which, though relatively small in size, possess reasonable mass and adequate strength characteristics to operate at very high rotational speeds. Sufficient energy can be obtained to propel a transit bus between charging stations. Such stored energy, plus that obtained by "capturing" kinetic energy during braking cycles, can also be used for load leveling, thus significantly improving fuel efficiency.

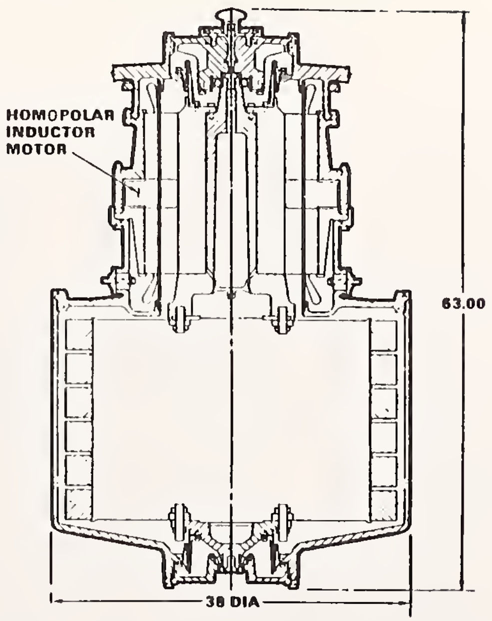
Flywheel technology development has included investigation into areas such as high strength steels, fiber composite materials, combination of materials, disks in various design configurations, testing methods, bearing designs, lubrication systems, vacuum subsystems, seals, and rotor containment consideration. During this technical development period, the flywheel has evolved as a mechanical energy storage device that can act not only as a vehicle back-up propulsion system, but also as the prime propulsion system. Figure 7 provides technical data on three representative flywheel designs. The G.E. and Garrett flywheels were to have storage capacities large enough to move the vehicle as primary propulsion systems. Currently, the Garrett flywheel is being redesigned to reduce its rotational speed and storage capacity. The Volvo design illustrates the category of flywheels, developed mostly in Europe, that are useful for load leveling.

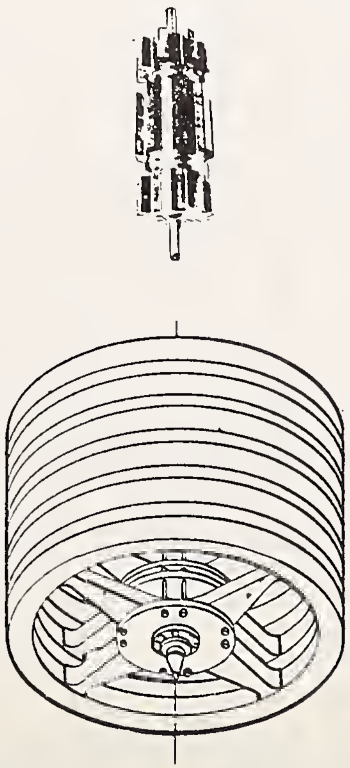
The energy density of flywheel systems is somewhat greater than that of hydraulic accumulators and roughly the same as that of battery systems. The flywheel has no fundamental limitation on charge or discharge time, has a very long life cycle, does not degrade with age, and is less affected by temperature. Composite flywheels, possible using modern technological advances, have the potential for very high specific energy designs, but these levels are achieved only at very high rotational speeds.

GENERAL ELECTRIC STEEL FLYWHEEL

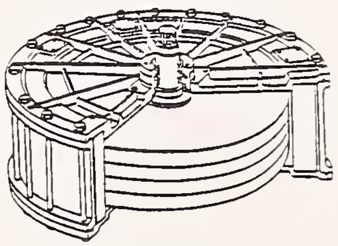


GARRETT COMPOSITE FLYWHEEL





VOLVO STEEL FLYWHEEL



	G.E.	GARRETT	VOLVO
SPEED (rpm)	5750 to 11,500	8000 to 16,600	6800 to 8000
STORAGE (kW-hr)	12 to 6	4 to 16.1	2.3
SPECIFIC ENERGY (W/#)	9.8	15.1	3.2
FLYWHEEL			
(a) NO. OF DISKS (n)	6 (Steel)	6 (Composite)	4 (Steel)
(b) WEIGHT OF FLYWHEEL ASSEMBLY (lb)	1450	750	726
(c) SAFETY (CONTAINMENT)	1.7" Steel Band	Kevlar-49/ Epoxy Outer Flywheel Rim	2.25" Steel Band
MOTOR	Homo Polar	Homo Polar	Diesel Engine/ Hydrostatic Motor
HOUSING	Welded Alum.	Welded Alum.	Cast Iron
COOLING	Liquid	Liquid	----

FIGURE 7. THREE REPRESENTATIVE ENERGY STORAGE FLYWHEEL DESIGNS

With present manufacturing techniques, the steel flywheel can be manufactured and assembled to tolerances in which the dynamics of disk rotation are less of a problem, whereas the composite wheel requires special care in assembly and testing. Additional detail on commercial application of flywheel energy storage systems is given in Section 3., Hybrid Systems.

2.4.2 Hydraulic Accumulator

A second mechanical (hydraulic) energy storage device that has been applied to augmenting the primary bus propulsion system is the hydraulic accumulator. The following general description is representative of stored hydraulic energy propulsion (SHEP) systems.

Energy storage is accomplished in this system by compressing a pocket of gas in a pressure vessel, usually a cylinder, through the use of a hydraulic fluid. To reconvert the stored energy in the hydraulic accumulator a hydrostatic motor is used. In the past few years the hydrostatic variable displacement pump/motor (which acts as a continuously variable transmission) has been designed with efficiencies high enough to make the accumulator attractive as a mechanical energy storage system for buses. These high efficiencies generally occur over the full range of design operating speeds, torque and displacement. High efficiencies are possible by minimizing frictional losses through the use of hydrostatic bearings, low viscosity fluids and pressure balancing techniques. To minimize compressibility losses under conditions of reduced pump displacement, a bent axis axial piston design is used. This design uses a piston configuration in which the clearance volume does not increase as the piston stroke is reduced.

Unlike the flywheel energy storage system, which can be designed to have sufficient storage to act as a primary propulsion device, the hydraulic accumulator does not have the storage capacity to adequately perform over the average transit vehicle route profile. Therefore, the hydraulic accumulator most likely will remain as a limited auxiliary propulsion system offering potential fuel economy benefits. The fuel economy advantages of the hydraulic accumulator, as well as those of the flywheel, come from two areas:

- The hydraulic accumulator reclaims and uses energy normally lost during vehicle braking.

- The accumulator augments the primary propulsion system, thereby permitting possible down-sizing of the primary system for operation at or near optimum efficiency (load-leveling feature).

This latter design option is possible since the accumulator can provide the initial high energy surge necessary to accelerate the transit bus at a time when the primary power source is least efficient.

2.4.3 Summary of Mechanical Energy Storage Devices

The important characteristic of mechanical energy storage systems is their ability to store and provide energy at a rate compatible with the operating needs of the transit coach drive cycle. The mechanical energy storage systems can perform this energy storage and retrieval cycle repeatedly without degradation. When used in a drivetrain as a load-leveling device, the overall system efficiency is improved with no sacrifice in performance. The development of an infinitely variable transmission (IVT) that is more efficient, reliable and inexpensive has been crucial to the application and commercial development of mechanical energy storage systems. More detailed discussion of prototype and commercial applications of these systems is provided in Section 3.0.

3. HYBRID PROPULSION SYSTEMS

3.1 GENERAL

Hybrid propulsion systems are comprised of combinations (usually two) of individual propulsion systems. Typically one of the propulsion systems will be more conventional, such as a diesel engine or electric motor supplied by an overhead wire. Generally, there are three categories of hybrid propulsion systems designed for use in urban transit buses - dual power, auxiliary power, and load-leveling systems.

The dual powered bus has two distinct means of propulsion, used one at a time. Both are designed to fully power the bus and its accessory loads (heating, lighting, ventilation or air conditioning, compressed air, etc.) when operating. The performance of the two systems may differ, each optimized for its part of the operating profile, but each is capable of adequate acceleration and speed for normal operations.

A hybrid system featuring an auxiliary propulsion device operates under normal revenue service totally on its primary propulsion source and switches to a back-up source only for emergency purposes or for maintenance yard movement of the coach. Auxiliary power is only back-up and as such is not capable of driving many accessories (such as air conditioning) nor is it capable of meeting normal speed or acceleration power requirements.

Hybrid propulsion systems using load-leveling devices, such as mechanical energy storage devices, reclaim, store and apply energy obtained during braking of the vehicle. They are called load-leveling since they are usually operative during acceleration when the greatest load is on the propulsion system These systems can be designed to operate independently from, or together with, the main propulsion system.

These categorizations are useful for discussion purposes only since in reality there are numerous design variations having performance characteristics that differ from those of more typical dual, auxiliary and

TABLE 2. SUMMARY OF HYBRID PROPULSION TECHNOLOGY - WORLDWIDE

QUANTITY	OPERATING COMMUNITY	COUNTRY	COMMISSIONING DATE	CHASSIS BUILDER	COACH BUILDER	VEHICLE TYPE (SEE FIG. 2)	VEHICLE LENGTH FT. (M)	SEATS STANDEES	PRIMARY PROPULSION TYPE/MFR	PRIMARY RATING KW (V)	PRIMARY SPEED MAX. MPH (KPH)	SECONDARY PROPULSION TYPE/MFR	SECONDARY RATING	SECONDARY SPEED MAX. MPH (KPH)	BRAKING	ELECTRICAL CONTROL	GVW LBS. (KG.)
	DUAL HYBRID																
600	New Jersey Transit	USA	1930	Mack	Yellow	2 Axle	35.0 (10.7)		ET/			C					
1	Univ. of Florida	USA	1977	Electrobus	Electrobus	2 Axle	24.0 (7.3)	14 (16)	B/ELECTROBUS	30 (100)	40 (65)	DG	630 AH		Air/Hyd.	C	17,500
13	Stuttgart	Germany	1979	Mercedes	Mercedes	2 Axle	36.4 (11.1)	35 (65)	DG/BOSCH	115 (360)	42 (70)	B/VARTA	104 KWH		Regenerative	C	41.800 (19,000)
7	Wesel	Germany	1979	Mercedes	Mercedes	2 Axle	36.4 (11.1)	35 (65)	DG/BOSCH	115 (360)	42 (70)	B/VARTA			Regenerative	C	41,800 (19,000)
2	Esslingen	Germany	1979	Mercedes	Mercedes	2 Axle	36.4 (11.1)	35 (65)	ET/BOSCH	115 (600)	42 (36)	B			Regenerative	C	41,360 (18,800)
2	Esslingen	Germany	1980	Mercedes	Mercedes	2 Axle	36.4 (11.1)	35 (65)	ET/BOSCH			DG/D-B					
2	Esslingen	Germany	1981	Mercedes	Mercedes	Artic	59.0 (18.0)		ET/BOSCH			DG/D-B					
15	Esslingen (Proposed)	Germany	1983	Mercedes	Mercedes	Artic	59.0 (18.0)		ET/BOSCH			DG/D-B					
.1	Fiat Experimental	Italy	1976	Iveco	Maur	2 Axle	36.4 (11.0)	15 (70)	DG/H.A.	90 (600)	39 (30)	B	135 AH	'	Regenerative	C	
1	DTT	France	1981	Renault	Renault	Artic	57.7 (17.6)	55 (90)	ET/BBC	200 (600)	36 (60)	B/BBC	200 KW	30 (50)	Regenerative	C	61,600 (28,000)
1	Tours	France	1983	Citroen	Heuliez	2 Axle*	20.0 (6.0)	9 (14)	D/CITROEN	50	65 (108)	B/HEULIEZ	25 KW	30 (50)	Power Asst. Hyd.	C	12,200 (5,550)
48	Nancy	France	1982-83	Renault	Renault	Artic	57.7 (17.6)	41 (112)	ET/BBC	190	36 (60)	DG/RVI	166 KW	36 (60)	Regenerative	C	61,600 (28,000)
8	Grenoble, Lyon St. Etienne	France	1982-83	Renault	Renault	2 Axle	36.7 (11.2)	35 (58)	ET/BBC	118 (600)	36 (60)	DG/RVI	40 KW	18 (30)	Regenerative	C	35,400 (16,000)
1	San Francisco (Test)	USA	1983	Flyer Ind.	Flyer	2 Axle	40.0 (11.2)	42 (46)	ET/BBC	184 (600)	55 (92)	F/GARRETT	16 KWH		Regenerative	C	
1	Seattle	USA	1982	Renault	Renault	Artic	59.0 (18.0)	70 (35)	ET/CEM	190 (600)	36 (60)	D/RENAULT	245 HP	30 (50)	Regenerative	C	57,800 (26,300)
	AUXILIARY HYBRID																
101	Zurich(31)Bern(32)Basle(10) Geneva(42)Neuchatel(10)	Switzerland	1974-75	FBW	FBW	Artic	57.1 (17.4)	44 (118)	ET/BBC	166 (600)	36 (60)	PG/BBC	49 KW	18 (30)	Rheostatic	C	60,060 (27,300)
50	Grenoble	France	1978	Renault	Renault	2 Axle	36.9 (11.23)	35 (58)	ET/BBC	130 (600)	36 (60)	DG/DEUTZ	58 HP	20 (32)	Magnetic	ER	38,400 (17,500)
110	Lyon	France	1975-79	Renault	Renault	2 Axle	36.9 (11.23)	35 (58)	ET/BBC	130 (600)	36 (60)	DG/DEUTZ	58 HP	20 (32)	Magnetic	ER	38,400 (17,500)
25	St. Etienne	France	1978	Renault	Renault	2 Axle	36.9 (11.23)	35 (58)	ET/BBC	130 (600)	36 (60)	DG/DEUTZ	58 HP	20 (32)	Magnetic	ER	38,400 (17,500)
4	Bergen	Norway	1978	Volvo	Hess	2 Axle	36.9 (11.23)	35 (35)	ET/BBC	169 (600)	36 (60)	PG/BBC	49 KW	21 (35)	Regenerative	C	35,400 (16,090)
1	Budapest (Now in USA)	Hungary +	1979	Ikarus	Ikarus	Artic	54.1 (16.5)	35 (66)	ET/BBC	169 (600)	36 (60)	PG/BBC	49 KW	20 (32)	Magnetic	C	49,500 (22,500)
1	Sao Paulo	Brazil	1979	Mercedes	Mercedes	2 Axle	36.4 (11.11)	35 (64)	ET/BBC	106 (600)	36 (60)	PG/BBC	49 KW	14 (29)	Regenerative	ER	39,600 (18,000)
1	Helsinki	Finland	1979	Suomen	Wiima	2 Axle	39.4 (12.0)	37 (65)	ET/STROMBERG	100 (600)	36 (60)	DG	40 KW	27 (45)	Regenerative	C	39,600 (18,000)
7	Bienne	Switzerland	1980	FBW	R & J	2 Axle	39.4 (12.0)	33 (54)	ET/BBC	140 (600)	36 (60)	PG/BBC	49 KW	24 (40)	Regenerative	C	39,600 (18,000)
2	Bergen	Norway	1980	M.A.N.	G & S	Artic	59.0 (18.0)	49 (83)	ET/BBC	140 (600)	36 (60)	PG/BBC	49 KW	18 (30)	Magnetic	C	55,000 (25,000)
45	Marseille	France	1980	Renault	Renault	2 Axle	36.9 (11.23)	35 (58)	ET/BBC	130 (600)	36 (60)	PG/BBC	58 HP	20 (32)	Magnetic	C	38,400 (17,500)
1	Johannesburg	So. Africa	1981	Mercedes	Mercedes	2 Axle DD		90 (9)	ET/BBC	140 (600)	40 (65)	PG/BBC	49 KW	18 (30)	Regenerative	C	37,900 (17,230)
1	Johannesburg	So. Africa	1981	Sigma	Sigma	2 Axle DD		90 (9)	ET/BBC	140 (600)	40 (65)	PG/BBC	49 KW	18 (30)	Regenerative	C	37,900 (17,230)
20	Lausanne	Switzerland	1981-82	FBW	Hess	2 Axle*			ET/BBC			PG/BBC				C	
3	Bergen	Norway	1982	Mercedes	Mercedes	Artic	57.1 (17.4)	60 (100)	ET/BBC	172 (600)	40 (65)	PG/BBC	49 KW	21 (35)	Rheostatic	C	55,660 (25,300)
15	Limoges	France	1982-83	Renault	Renault	2 Axle			ET/BBC			PG				C	
12	Neuchatel	Switzerland	1983-84	FBW	Hess	Artic			ET/BBC	166 (600)	36 (60)	PG/BBC	49 KW	18 (30)	Regenerative	C	57.640 (26,200)
	HYBRID FOR INITIAL ACCELLERATION ONLY																
1	Daimler Benz Gyro Drive	Germany	1981	Mercedes	Mercedes	2 Axle			D/MERCEDES	48		F	750 WH				
1	M.A.N. Hydrobus	Germany	1981	M.A.N.	M.A.N.	2 Axle			D/M.A.N.			H					
1	M.A.N. Gyrobus	Germany	1981	M.A.N.	M.A.N.	2 Axle			D/M.A.N.			F					
8	St. Gallen	Switzerland	1971	Saurer	Saurer	2 Axle			ET/BBC			B				C	
4	Lugano	Switzerland	1974	Volvo	Hess	2 Axle	37.7 (11.5)	23 (76)	ET/BBC	165 (1000)	36 (60)	B			Rheostatic	ER	
4	Lugano	Switzerland	1974	Volvo	Hess	Artic	37.7 (11.5)	23 (76)	ET/BBC	165 (1000)	36 (60)	B			Rheostatic	ER	
18	Lausanne	Switzerland	1974-75	FBW	FBW	2 Axle*	74.5 (22.7)	68 (106)	ET/BBC	166 (600)	36 (60)	B			Rheo. & Air	C	68,200 (31,000)
1	Gothenburg (Test)	Sweden	1980	Volvo		2 Axle	39.4 (12.0)		DG/	100 HS	48 (80)	P	125 KW	48 (80)	Regenerative	N/A	36,300 (16.500)
1	Copenhagen (Test)	Denmark	1981	D.A.B.		2 Axle	33.1 (10.1)		D/								

+Crown Coach Demo

*With coupled trailer

R & J=Ramsier & Jenser
G & S=O.A.F. Graef & Stift
Div. M.A.N.
FBW=Aktiengesellschaft Franz
Brozincevic & Co.
BBC=Brown Boveri Group
M.A.N.=Maschinenfabrik Augsberg
Nürnberg Aktiengesellschaft
RVI=Renault Véhicules Industriels
CEM=Creusen Elektro-Mechanische
Industrie b.v.
D-B=Daimler-Benz

DD=Double Decker
ET=Electric Trolley
D=Diesel
HS=Hydrostatic
B=Batteries
PG=Gasoline Generator
DG=Diesel Generator
F=Flywheel
H=Hydraulic Accumulator
G=Gasoline Engine
ER=Electronic Resistor
C=Chopper
HR=Hybrid Resistor

load-leveling systems. Table 2 provides technical information on hybrid propulsion systems identified worldwide. The technology discussed in this section represents the major European and domestic activity for which information was readily available. In addition, the extent of technical detail provided in subsequent paragraphs unfortunately varies somewhat from system to system. Again, this was dependent on quality and quantity of information in responses to requests for information from manufacturers.

3.2 DUAL POWER

Virtually all successful developments of dual-power, hybrid propulsion vehicles have been based on the trolley bus and the electric motor system. Since many European cities still maintain relatively large trolley coach fleets* compared to the U.S., it is understandable that most technology advancements have their basis in European research and manufacturing. The technology advancements in dual-power systems involve, in general, overhead, utility-based power for the electric traction motor in conjunction with either:

- Diesel engine
- Battery (as an alternate electrical source)
- Flywheel

3.2.1 Trolley/Diesel

Since the trolley bus and diesel bus are the most successful existing bus types, there has been a tendency to combine these two systems in a hybrid vehicle. Operating on-wire, the vehicle is quiet and non-polluting, and is able to climb hills well. Using the diesel-powered generator, it is able to operate without benefit of overhead wires on any street, while its high top speed allows use on express roads and freeways.

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*See "The Trolley Coach Development and State of the Art, Task 1 Report", prepared for U.S. Department of Transportation, Urban Mass Transportation Administration, by Chase, Rosen & Wallace, Inc., October 1979, NTIS #PB80-104870.

The only known large fleet of hybrid buses was of this general type. Public Service Coordinated Transport (PSCT - now NJ Transit Bus Operations) experimented around 1930, adding current collectors to gasoline-electric buses. At that time, gasoline buses were available with electric drive because automatic transmissions had not been developed. Figure 8 illustrates this dual-powered design. The test was a success, and Public Service Coordinated Transport replaced large quantities of streetcars with these buses, which operated under wire where it was available and by gas engine-generated electricity elsewhere. Eventually the fleet of "All Service Vehicles" reached about six hundred, four hundred of which were built new by Yellow Coach (now GMC) and the rest converted from gas-electrics. Figure 9 shows pictures of this bus in operation.

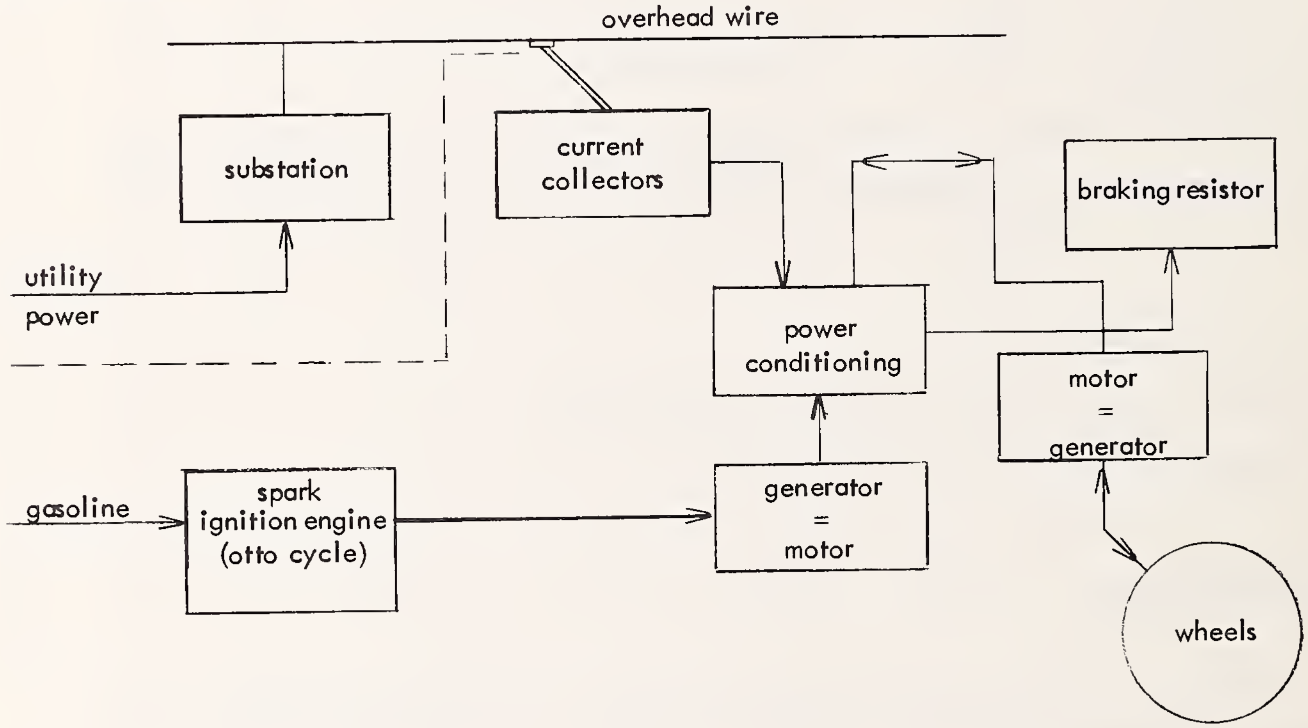


FIGURE 8. TROLLEY BUS WITH GASOLINE AUXILIARY ENGINE

Powered by
Gasoline
Generator

Powered by
Utility

FIGURE 9. TROLLEY/GASOLINE GENERATOR HYBRID PROPULSION - PUBLIC SERVICE COORDINATED TRANSPORT COACH

More recently, vehicle propulsion designs by Daimler-Benz (Mercedes) and by Renault have gotten away from the use of gas/diesel-powered generators. Instead they incorporate two separate propulsion drives, a diesel engine driving through an automatic transmission and the electric traction motor powered from the overhead wire system. The schematic of the dual-powered, diesel/trolley bus is provided in Figure 10.

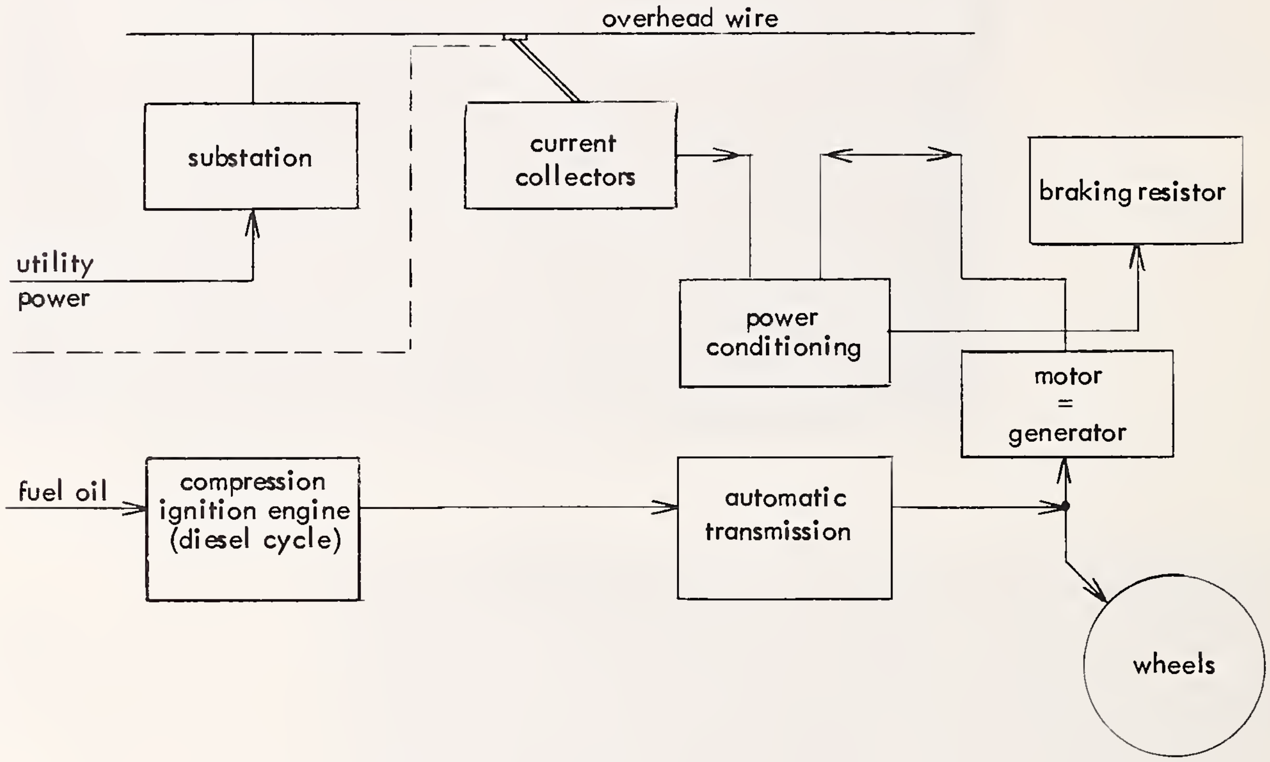


FIGURE 10. DIESEL-TROLLEY DUAL-POWERED BUS - RENAULT

As part of a German research project, Mercedes produced three prototype trolley/diesel buses, two of them a 2-axle type and one articulated. They have been extensively tested in Esslingen, a suburb of Stuttgart. Mercedes currently offers its trolley/diesel bus in either the standard size coach or in an articulated coach. The standard size bus configuration is shown in Figure 11.

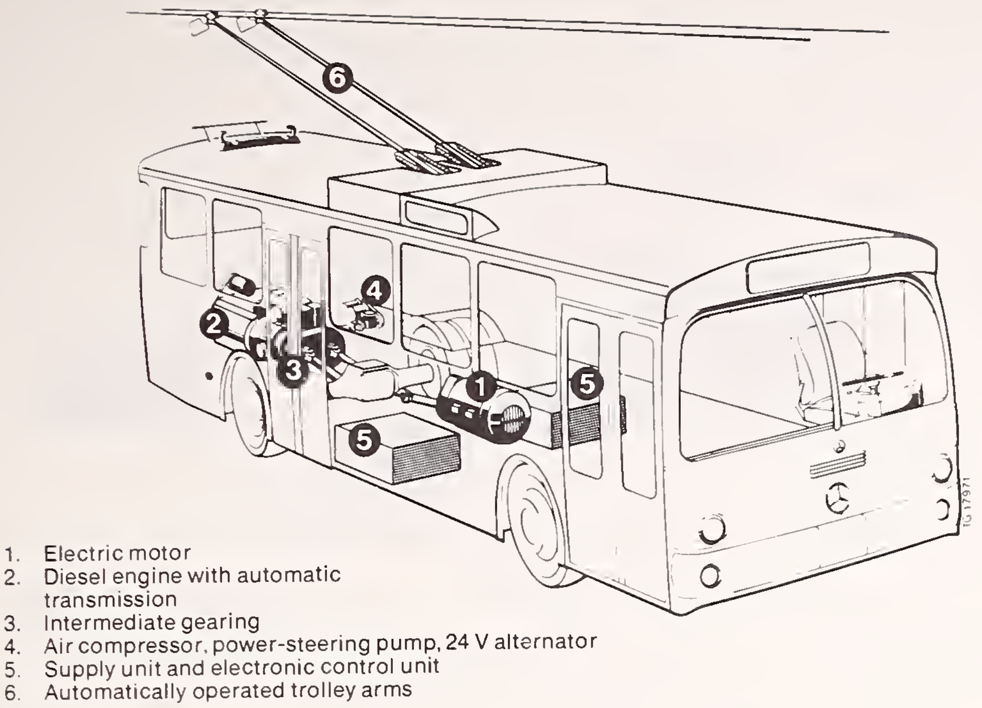


FIGURE 11. MERCEDES STANDARD SIZE TROLLEY/DIESEL BUS COACH

Mercedes promotes this bus as a means to extend trolley routes or to avoid trolley route blockages. Propulsion energy can be taken from the overhead wires with the trolley arms being automatically controlled from the driver's seat. Where there are no overhead wires, the bus is directly driven by a conventional diesel engine through an automatic gearbox. The electric motor also acts on the drive axle via the gearbox. Accessories, such as the air compressor, alternator and power steering pump, are driven from the transfer case, which is mounted between the engine and the gearbox.

Figure 12 provides a different view of the Mercedes design. When the driver selects the diesel engine, the electric motor is disengaged and power is transmitted from the diesel engine to the drive axle via the clutch, transfer case and gearbox. When using the electric drive, the diesel engine is switched off, the clutch between the diesel engine and transfer case is disengaged and the clutch between the electric motor and transfer case is engaged.

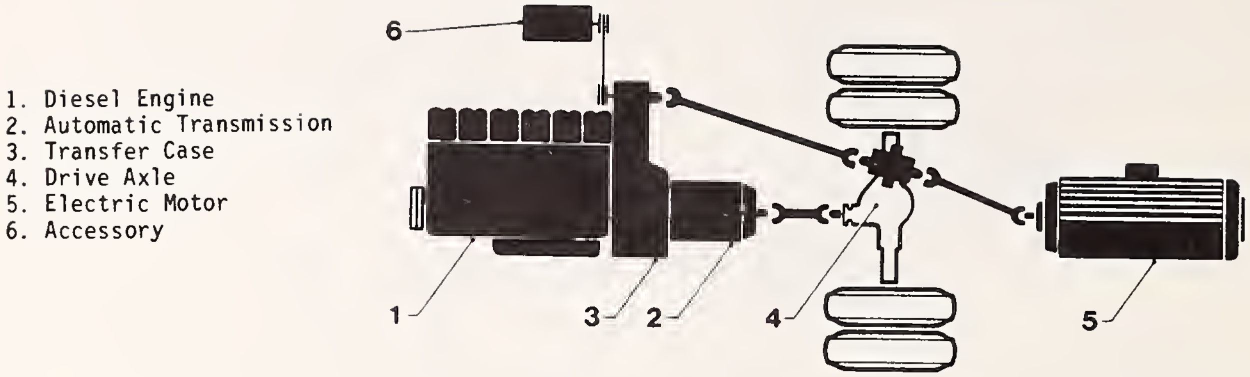


FIGURE 12. SCHEMATIC OF MERCEDES TROLLEY/DIESEL COACH

The Mercedes articulated trolley bus offering the dual propulsion (electric trolley/diesel) is shown in Figure 13.

FIGURE 13. MERCEDES ARTICULATED TROLLEY/DIESEL BUS

Renault is producing 48 PER 180-type articulated hybrid vehicles for the Urban District of Nancy (France); one of these production vehicles is in Seattle for testing. These buses have a diesel engine and an electric traction motor. There is, of course, a weight penalty when two complete propulsion systems are placed in a bus. The Renault dual-powered articulated bus in Seattle has an empty weight of 42,800 pounds, compared with about 36,000 for Seattle's diesel, non-hybrid articulates.

Renault's PER 180 is characterized as a parallel hybrid. The two driving axles can be powered by the electric motor or by the diesel engine. The diesel drive is the same 225 horsepower (166 kW @ 2400 rpm) engine used on the standard-size Renault bus. The electric drive includes a 240 horsepower motor which is controlled by a Freon-cooled DC chopper. The performance of the PER 180 hybrid articulated carrying a full load of 165 passengers is reported by Renault to be:

	Vehicle on Electric Traction Motor	Vehicle On Diesel
Max. Speed	37 mph (60 km/h)	37 mph (60 km/h)
Speed on a 6% Grade	25 mph (40 km/h)	14 mph (22 km/h)
Speed on an 8% Grade	22 mph (35 km/h)	12 mph (19 km/h)

Figure 14 shows the general layout of the Renault PER 180 drive train.

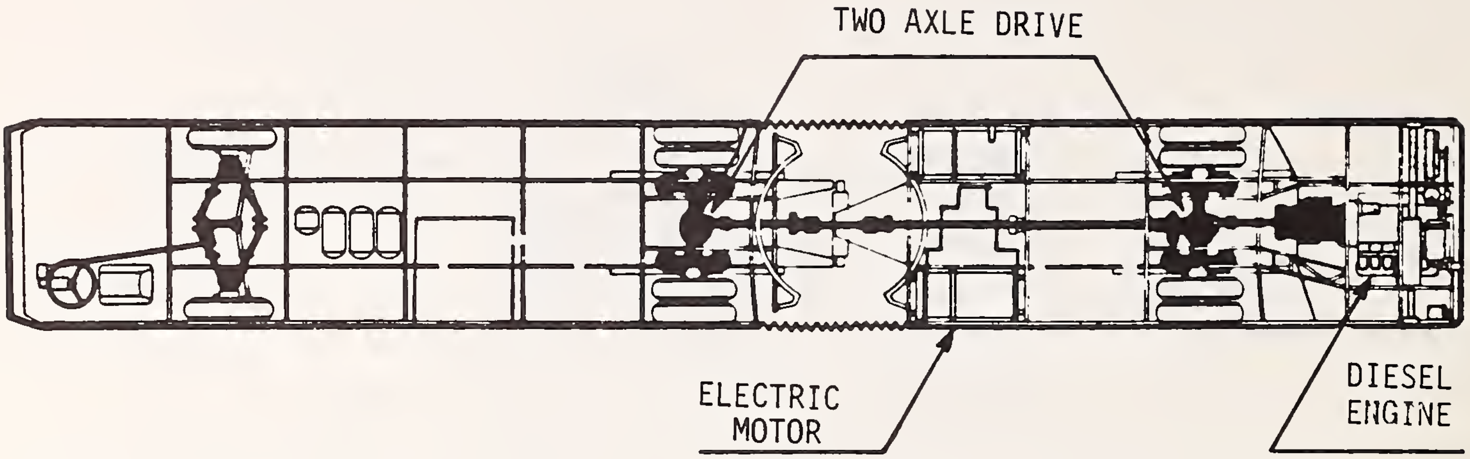


FIGURE 14. RENAULT DUAL-POWERED ARTICULATED TROLLEY COACH

The Renault Truck and Coach Division officially presented this vehicle to French Transport authorities late in 1981. The bus as configured for the Seattle demonstration is shown in Figure 15.

FIGURE 15. RENAULT DUAL-POWERED BUS AS CONFIGURED FOR SEATTLE DEMONSTRATION

3.2.2 Trolley/Battery

Equipping a trolley coach with a large battery enables it to operate off-wire at normal speeds with a range of several miles. For the research project in Esslingen, Mercedes produced three standard-size trolley/battery buses. An older bus was converted and tested, then two second-generation vehicles were built. The battery is a lead-acid type rated at 360 V, 230 ampere hours (83 kilowatt hours theoretical capacity), weighing 3 metric tons. Off-wire route capability is reportedly over six miles. Because rapid cycling of the battery generates considerable heat, a liquid cooling subsystem for the battery was developed. When operating on-wire, the battery remains connected to the system, storing braking energy and acting as a load-leveler. This propulsion configuration is shown in Figure 16.

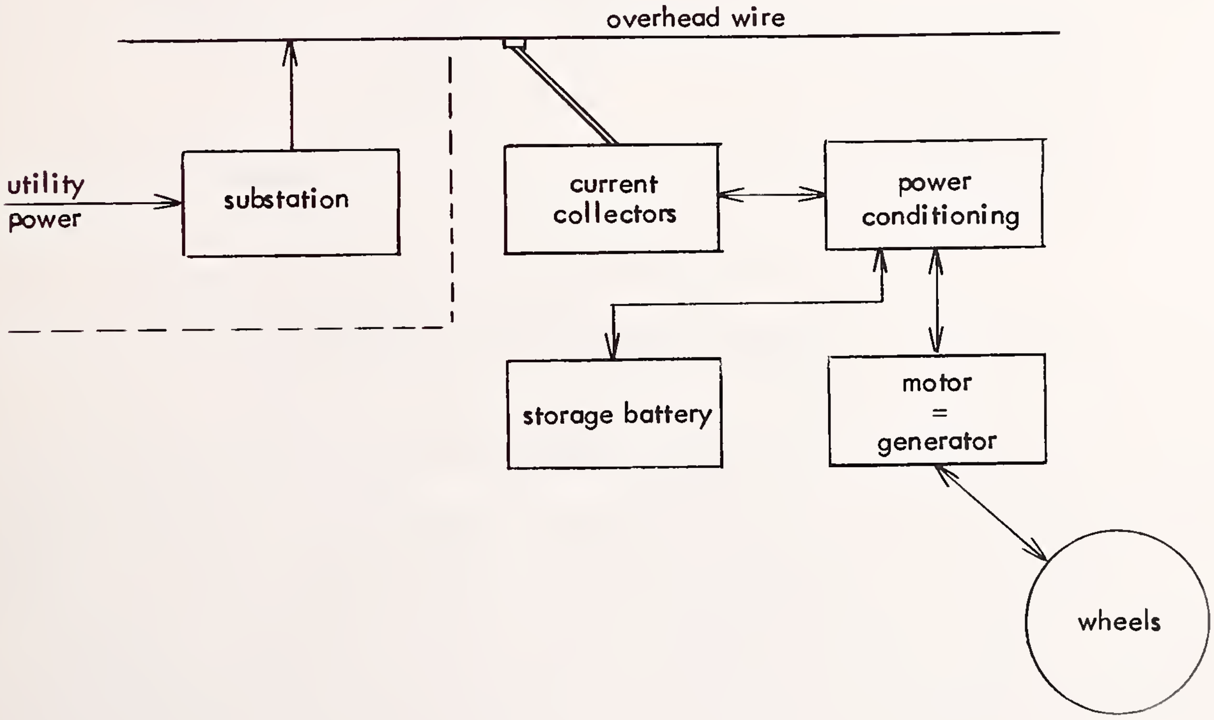


FIGURE 16. TROLLEY BUS WITH BATTERY AUXILIARY POWER

The Mercedes 0305 trolley/battery bus uses an electric propulsion motor as its primary power source. Two auxiliary power units drive the accessory equipment such as air compressor, generator, steering pump, etc. Figure 17 shows the general layout of the Mercedes dual-powered hybrid bus.

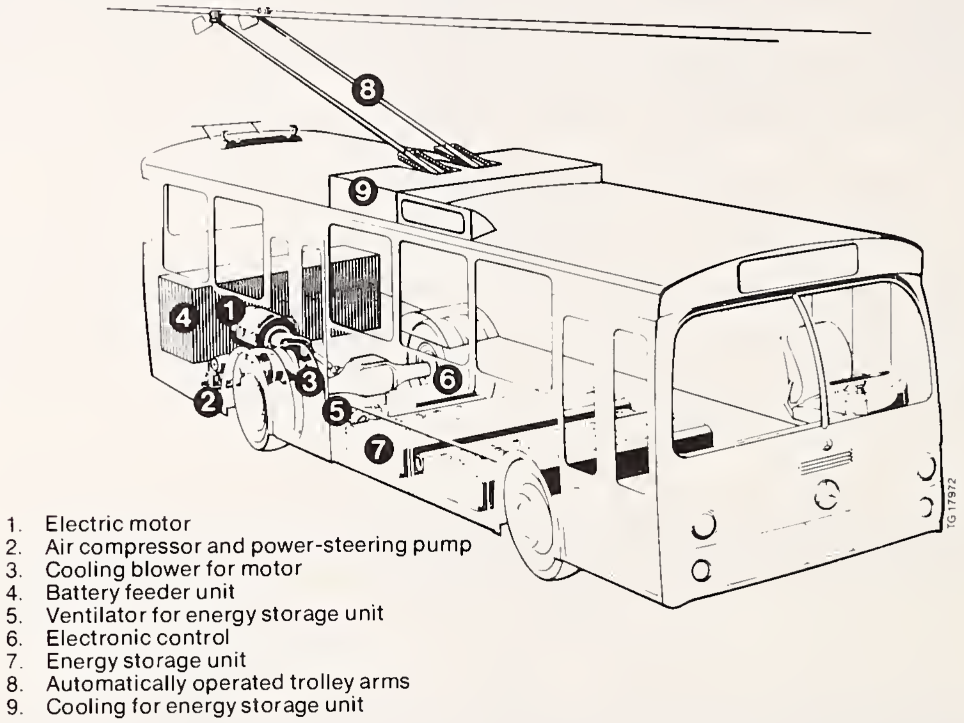


FIGURE 17. MERCEDES DUAL-POWERED HYBRID BUS

Renault also has developed a prototype trolley/battery bus, using a nickel-cadmium battery. This type of battery, while high in initial cost, has a long life and can be recharged rapidly. Renault has done full scale simulation which shows that the battery would have a lifetime of over 30,000 cycles, equivalent to at least five years operation in typical urban transit service. As with the Mercedes prototypes, the system stores energy recovered from braking, in the battery, and does load-leveling when operating on-wire. The range of the Renault bus is reportedly about three miles off-wire at zero grade.

The Renault dual-powered, trolley/battery bus, Model ER 180, is scheduled for production in 1984/85. The prototype bus was tested for a few months recently in the city of Lyon, France. The reported performance for a fully-loaded coach is shown below.

	Vehicle on Battery	Vehicle on Wires w/ Battery Charging	Vehicle on Wires w/o Battery Charging
Max. starting gradient	13%	13%	13%
Max. speed on a 2% gradient	33 km/h	43 km/h	50 km/h
Max. speed on a 6% gradient	21 km/h	29 km/h	33 km/h
Max. speed (zero grade)	50 km/h	60 km/h	62 km/h

The battery technology of these two systems (Mercedes and Renault) reflects the state-of-the-art in battery technology; they are heavy and costly and, generally, with continuous cycling, have a lifetime of about three to five years at a maximum.

3.2.3 Trolley/Flywheel

A flywheel connected to an electric motor (which also serves as a generator) is functionally equivalent to a battery as an energy storage element. It has a longer lifetime, has no theoretical charge/discharge rate limitation (although self-discharge is in hours rather than months), is little affected by temperature, and generates some noise. A prototype flywheel unit with a rated storage of 16 kWh has been built and was under test by Garrett AiResearch under an UMTA program. Figure 18 illustrates the hybrid power arrangement. It was originally scheduled to be installed in a Flyer trolley bus body and tested in San Francisco in 1983. At this time, technical problems with the flywheel have caused the testing of this prototype system to be suspended. Garrett is currently redesigning the flywheel to operate with a lower storage capacity.

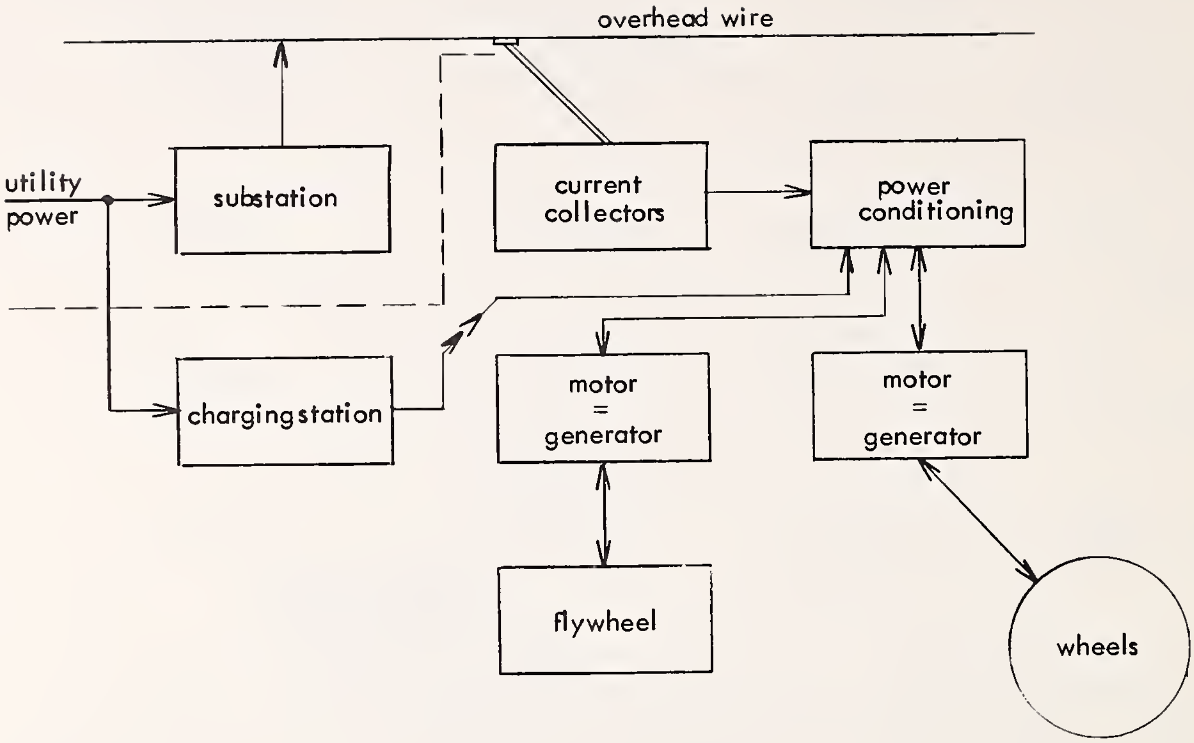


FIGURE 18. GARRETT FLYWHEEL TROLLEY BUS

3.3 AUXILIARY HYBRID

The conventional trolley bus has the disadvantage that it can travel only within the grid network of the electrification system. In case of a right-of-way blockage or a power failure, the vehicle becomes inoperative. Auxiliary hybrid buses, employing on-board back-up power, however, are able to move independently with limited speed, generally without supplying accessory loads. This capability is usually sufficient to meet most emergency situations and allows some electrification to be omitted in maintenance areas and for emergency turn-back loops. Obviously, there are trade-offs between sizing the auxiliary system and the associated performance. Specific limitations include poor performance on grades and limited braking, since accessory equipment, such as air compressors, are often not powered.

3.3.1 Trolley with Battery Auxiliary

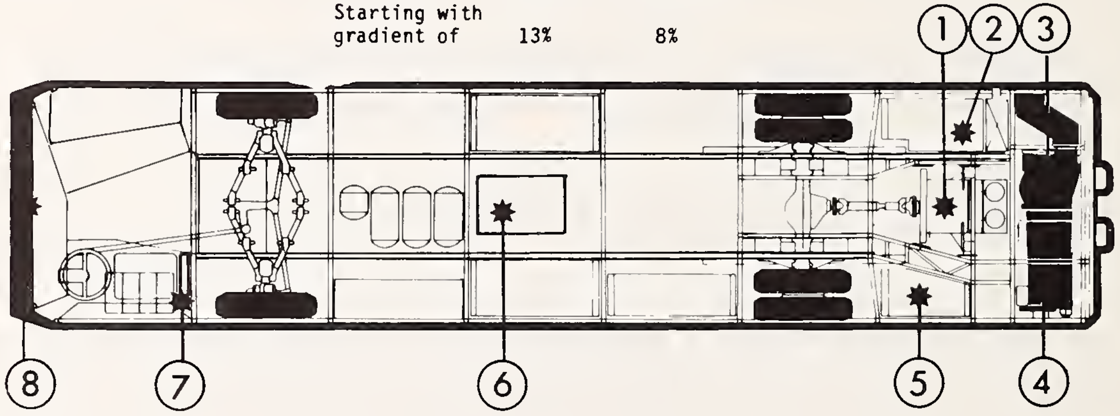
A lead-acid battery weighing 500 to 1000 pounds can propel a bus for about a mile or two at low speed. In one of the simplest applications, a 72 V battery is provided, with only an on/off control. The 600 V traction motor will move the bus at about 5 mph on level ground at this voltage. A means of recharging the battery while the bus is on-wire is also necessary. This system has low performance, but it is cheap and simple.

Garrett has built a prototype chopper system that enhances the auxiliary battery system. With a 72 V input, it can produce output from zero to 250 V so the bus will operate at speeds of up to about 15 mph under full control. The same chopper is used for battery recharging, taking power from the 12 V converter that charges the lighting battery. The system has been tested in Dayton, Ohio, using eight 12 V batteries. The bus reportedly met all performance requirements, including operating for a range of six miles.

3.3.2 Trolley with Engine-Generator Auxiliary

Compared to the battery auxiliary system above, a small gasoline or diesel engine-generator set can provide performance at least equal to the auxiliary chopper system and considerably greater in operating range. This design configuration represents the most common hybrid propulsion system. A popular European system is based on an air-cooled Volkswagen gasoline engine with a 30 kW generator and a five gallon tank. It can propel the bus at speeds of up to about 20 mph (at zero grade).

The Renault ER-100 trolley bus has a small air-cooled diesel engine with about twice the output of the Volkswagen system. This performs well enough to be used for limited route extensions off the electrification system. The drive train configuration and performance estimation of the Renault ER-100 is shown in Figure 19.



1 - Drive motor
2 - Power box:
  - drive, brake and auxiliaries switch
  - excitation chopper
  - reversing device
3 - Diesel engine
4 - Generator motor
5 - Relay logic box
6 - Rheostat (on roof)

PERFORMANCES
Vehicle under maximum load
With 1/13.66 rear axle drive ratio

	With overhead network	In independent operation
Maximum speed in the level	60 km/h	40 km/h
Speed reached after 5 sec.	15 km/h	6 km/h
10 sec.	35 km/h	10 km/h
15 sec.	45 km/h	12 km/h
Starting with gradient of	13%	8%

FIGURE 19. DRIVETRAIN CONFIGURATION AND ESTIMATED PERFORMANCE OF RENAULT ER-100

A system using a Volkswagen diesel engine is being built under an UMTA grant for testing in Boston (MBTA) and subsequent tests in San Francisco (MUNI).

3.4 MECHANICAL ENERGY STORAGE SYSTEMS FOR LOAD LEVELING

As discussed in Section 2.0, the typical bus energy consumption cycle demonstrates that transit bus propulsion systems can benefit by reclaiming and storing energy that is normally dissipated in braking for later use to assist during acceleration. Two promising non-electric energy storage systems, the flywheel and the hydraulic accumulator, have been developed and tested by European bus manufacturers. Simulated and actual tests indicate good performance results and sizable fuel savings when either is coupled with conventional transit propulsion systems.

3.4.1 Diesel with Auxiliary Flywheel Storage System

There are at least three major European truck and bus manufacturers who have conducted research and development on auxiliary flywheel propulsion systems*. They are:

- M.A.N. (Maschinenfabrik Augsburg - Nurnberg Aktiengesellschaft) Vehicle Division - Advanced Development, Germany
- Mercedes-Benz (Daimler-Benz Aktiengesellschaft), Germany
- Volvo (Volvo Flygmoter & Volvo Bus Corporation), Sweden

German research and development of hybrid systems for recovery of braking energy was sponsored initially by the German Federal Ministry of Research and Technology. In the case of M.A.N., the design of the hybrid propulsion unit is basically similar for both the flywheel and the hydraulic accumulator. The diesel engine drives an infinitely variable speed transmission (IVT) and the mechanical energy storage unit is also connected to the IVT input. The hybrid propulsion system has been tested in both a standard-size and a double decker coach. Figure 20 shows the M.A.N. standard-size coach incorporating the flywheel, load-leveling propulsion system.

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*Fiat is also known to have conducted research and development in flywheel propulsion systems. Unfortunately, very little information is available on their designs or status of development. Also, Detroit Diesel Allison (GMC) apparently has begun development and test of a propulsion system using a flywheel.

During braking the kinetic energy of the vehicle is transmitted from the wheels of the drive axle to the flywheel through the IVT. During vehicle acceleration the reverse process occurs. The diesel engine cuts in and out to keep the total of the accumulated and kinetic energy of the bus at a constant level. At constant speeds or on long inclines the diesel engine is the only means of propulsion. A diesel engine having about 1/3 less horsepower and weighing about 1000 pounds less than the usual engine is used. The flywheel unit weight (about 800 pounds) is almost the same as the engine weight savings. The lower drive power of the engine is compensated for by the reuse of stored energy.

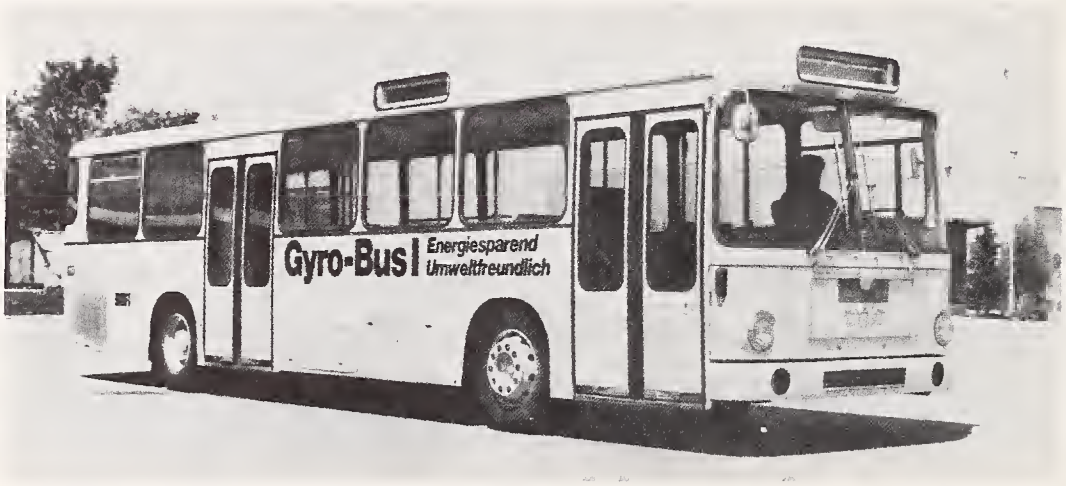

FIGURE 20. M.A.N. STANDARD-SIZE COACH INCORPORATING FLYWHEEL, LOAD-LEVELING PROPULSION SYSTEM

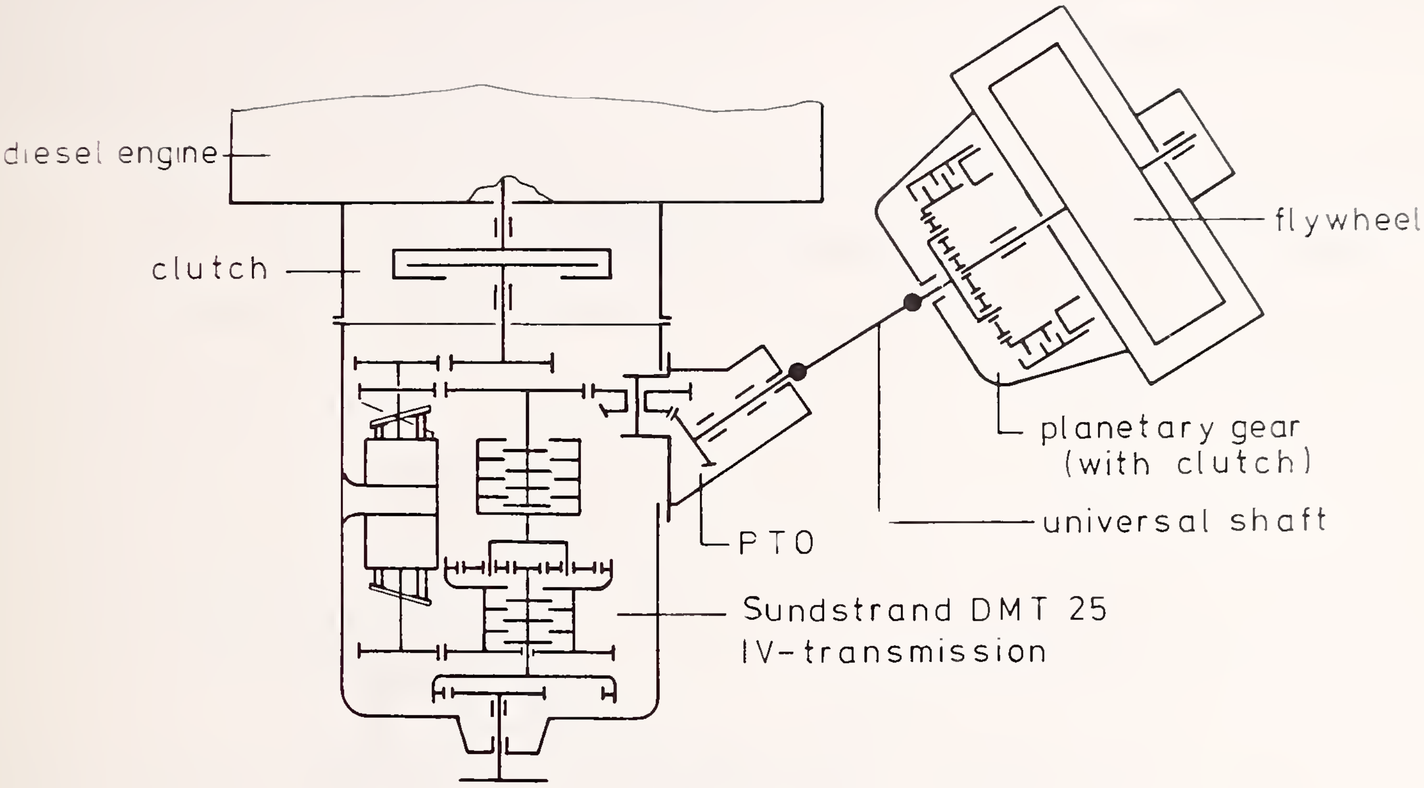

FIGURE 21. DRIVELINE OF GYROBUS I

The flywheel is connected to the power take-off shaft of the infinitely variable transmission as shown in Figure 21. The IVT has two drive ranges. The first range of the transmission is hydrostatic up to 20% of the output speed. The second drive range operates from both propulsion systems. In the M.A.N. Gyrobus II the engine and flywheel are connected by means of a differential so that full engine power is available during acceleration even when the flywheel speed is decreasing. M.A.N. reports a fuel savings relative to their standard diesel coach of between 8 and 16 percent; with continued developments planned, M.A.N. estimates savings of more than 20 percent.

Daimler-Benz has also developed a prototype flywheel auxiliary system in conjunction with the Technical University of Berlin, Bosch, M.A.N. and assistance from the Federal Ministry of Research and Technology. The configuration of the Mercedes-Benz 0305 Gyrodrive propulsion system is shown in Figure 22.

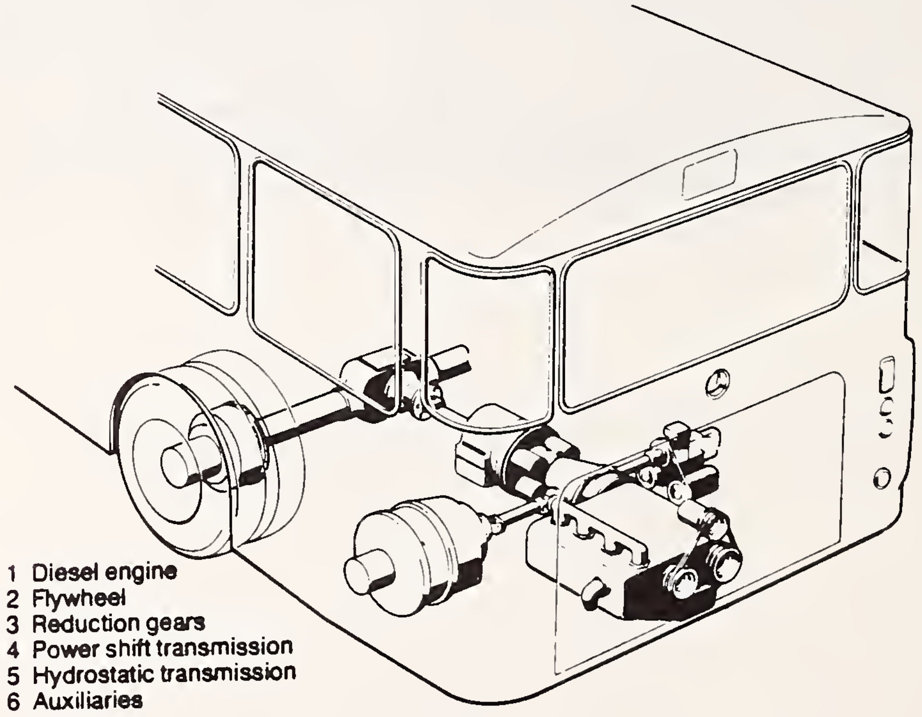

FIGURE 22. MERCEDES-BENZ O 305 GYRODRIVE URBAN BUS

The Mercedes design charges the flywheel during braking, or by surplus power from the engine during periods when propulsion requirements are low. Depending on the mode of operation, running power is supplied either by the diesel engine, by the flywheel or by both simultaneously. Mercedes makes claims of improved fuel economy, lower brake wear and lower performance requirements for the primary propulsion system, similar to those of M.A.N.

Volvo is another European manufacturer actively investigating auxiliary flywheel technology. Performance of the Volvo prototype in comparison to a standard Volvo bus propulsion system is as follows:

	Standard Volvo Propulsion System	Volvo Diesel/ Flywheel Design
Engine Power	160 kW	100 kW
Max. Accel. Power	160 kW	225 kW
Acceleration (0-30 mph)	13 sec	11 sec
Max. Speed	44-56 mph	44-56 mph
Fuel Consumption		75-85% of standard Volvo propulsion system

The use of the load-leveling system (flywheel) allowed the diesel engine rating to be reduced from 160 kW to 100 kW. Figure 23 shows the driveline configuration design of the Volvo bus.

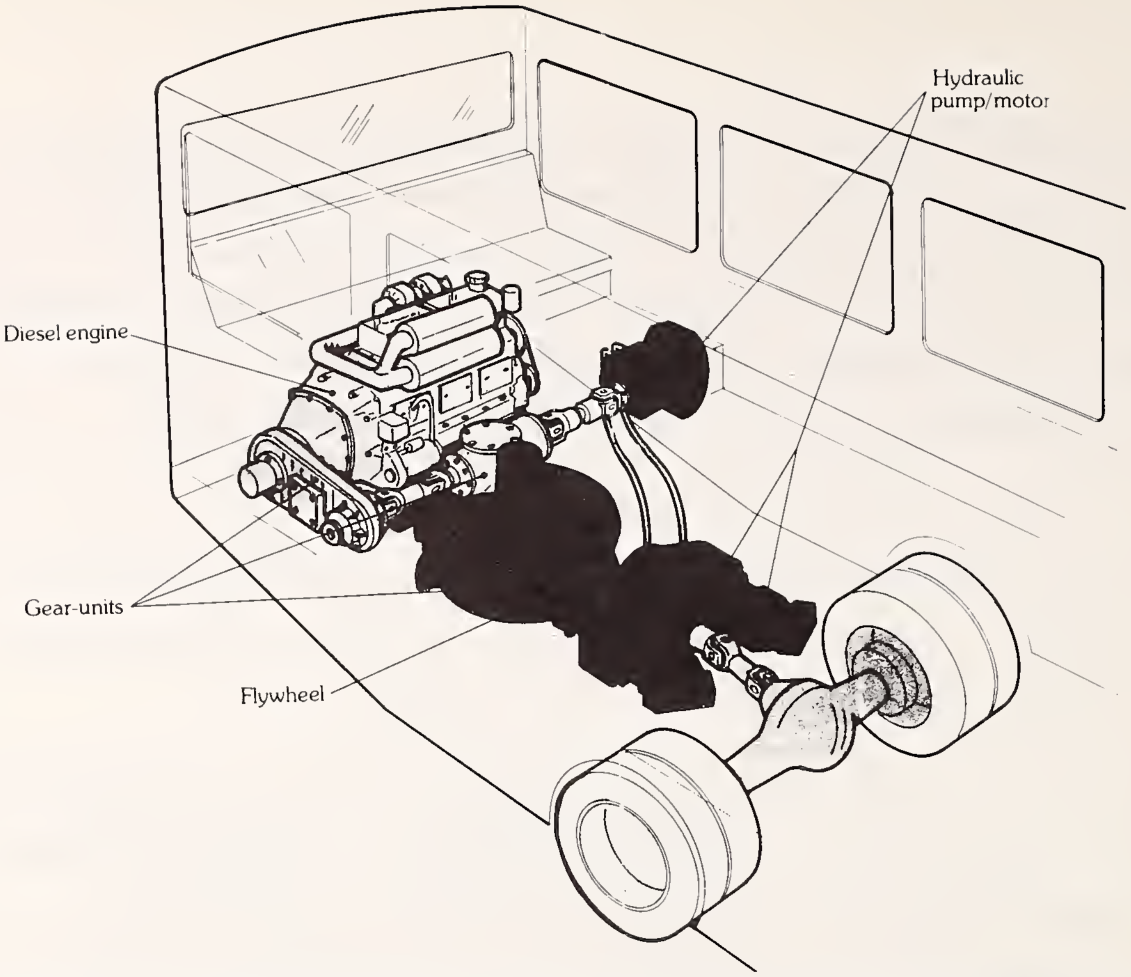

FIGURE 23. DRIVELINE CONFIGURATION OF VOLVO DIESEL/FLYWHEEL DESIGN

The Volvo flywheel design incorporates two clutches and two gear units in the mechanical connection of the engine to the flywheel. The flywheel itself has a storage capacity of 2.3 kWh which is sufficient to propel a 16-ton bus about 1100 yards, including three stops. High efficiency hydraulic pumps and motors are used. When the vehicle accelerates, the engine and the flywheel both contribute power.

3.4.2 Diesel With Hydraulic Accumulator

Another method of load leveling uses the hydraulic accumulator. Like the flywheel propulsion systems, it relies on a hydrostatic drive, but the energy is stored by using hydraulic fluid to compress a gas. The system is simpler than the flywheel system, but the amount of energy that can be stored is smaller. The diesel/hydraulic system is being tested by major vehicle builders such as Mercedes, M.A.N., Volvo and Fiat*, as well as by academic institutions such as the Technical University of Denmark.

Hydraulic accumulator propulsion systems can generally be categorized as serial or parallel.

Serial Arrangement

The serial configuration illustrated in Figure 24 consists of a hydraulic accumulator energy storage system in series with the drive system. There is no direct shaft linkage between the primary propulsion system and the driving wheels. The system consists of one hydrostatic pump connected to the primary propulsion system and a hydrostatic pump/motor providing power to the drive wheels. The second pump is used during retard and regenerative braking, whereas the motor is used to drive the wheels. The three units are adjusted, within the limits of the transmission gear ratio capabilities and the energy capacity of the accumulator, to obtain the desired torque and braking energy recovery performance at the drive wheels.

This process is controlled by a microprocessor which interprets driver commands and system feedback parameters in terms of a preprogrammed scenario based upon the capability of the complete hydraulic energy storage system.

The throttle is set for the most efficient engine performance. Due to the limited energy storage capacity of the hydraulic accumulator, the engine must be cycled on and off. The engine normally is off during vehicle acceleration and deceleration and is on when the accumulator is not fully

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*Little information was available on the Fiat technology.

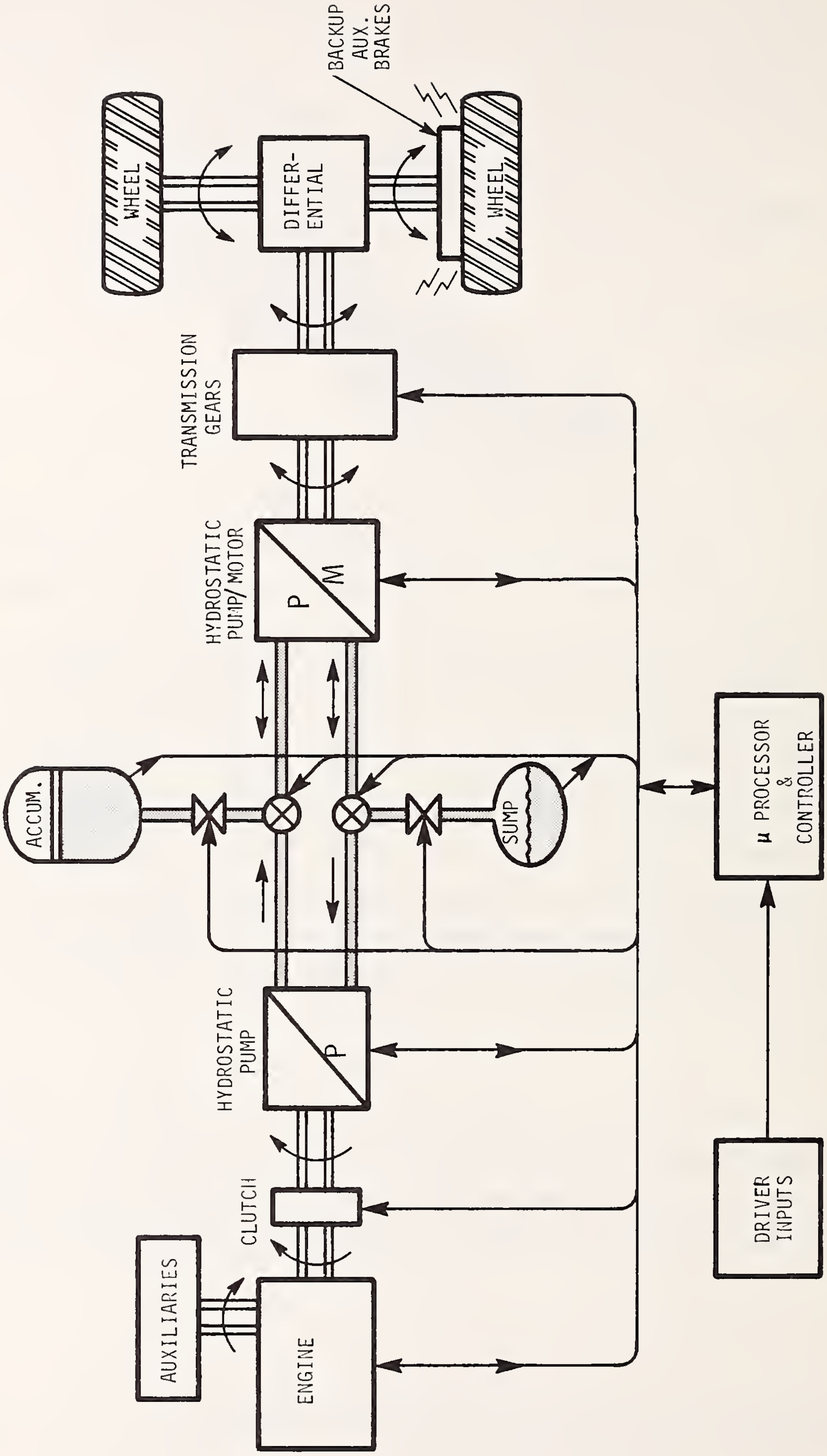

FIGURE 24. SERIAL HYDRAULIC ACCUMULATOR ENERGY STORAGE SYSTEM

charged. During vehicle cruise operation (maintaining constant speed), the vehicle uses a minimum of energy to sustain its speed. In this mode, the engine is intermittently cycled on and off. This cycling requires high accumulator pressures to minimize speed of engine on/off cycling. The use of a range of transmission gear ratios will decrease the engine duty cycle and the overall working pressure of the hydraulic energy storage system. The selection of the appropriate gear ratio for the drive leads to a more manageable energy storage system.

The serial arrangement is equipped with a bypass valve through which the hydraulic energy storage system can be bypassed. When the hydraulic storage system is bypassed, the engine drives the wheels through the hydrostatic pump/motor.

Two companies in the United States have been involved in the development of hydraulic accumulators in this serial configuration. They are:

a. Energy Research and Generation, Inc.
b. Advanced Energy Systems (Division of L.B. Nelson Corp.)

The Energy Research and Generation design concept uses a 100 gallon storage tank capable of storing 5 hp-hrs, and a Volvo hydraulic pump/motor. It is reportedly capable of accelerating a loaded bus at 4 mph/sec up to 30 mph with low noise levels. The storage tanks are fiberglass-wound storage bottles. The ERG system is still only a concept. The Advanced Energy System hydraulic accumulator was tested only in small passenger car applications during the late 1970s. It used fiberglass-wound storage bottles as in the ERG systems. This company is, however, reportedly no longer in business.

Parallel Arrangement

The parallel arrangement for hydraulic accumulator energy storage is characterized by two or more propulsion devices driving a single drive shaft. Figure 25 illustrates one arrangement in which the primary propulsion device is the diesel engine and the secondary driving device is the hydraulic accumulator in conjunction with the hydrostatic pump/motor.

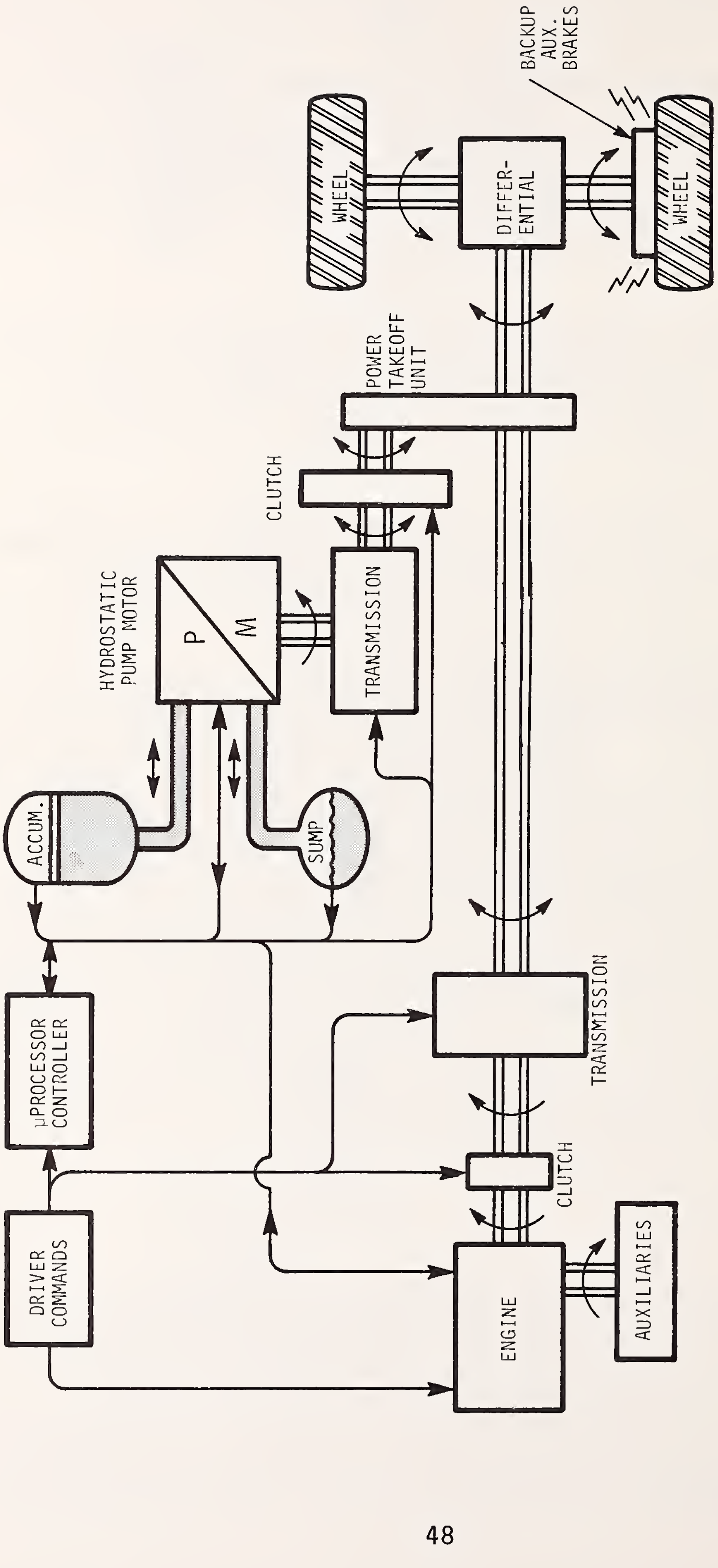

FIGURE 25. PARALLEL HYDRAULIC ACCUMULATOR ENERGY STORAGE SYSTEM

The advantage of the parallel arrangement is that the secondary power source can be added on as a modification to an existing propulsion system. The second advantage is that only one hydrostatic pump/motor is required, unlike the serial arrangement which requires at least a second pump.

In general, for optimum performance, a separate transmission gear box is employed for each propulsion device. When the engine is providing the power, it is coupled through the drive shaft to both the hydrostatic pump and the drive axle. By employing the appropriate gear ratio in the transmission, the engine may be operated at its most efficient point. When the hydraulic accumulator is fully charged (maximum pressure) the engine is de-clutched and the hydrostatic pump is switched to motor operation so that the rear axle of the bus is driven with the energy stored in the hydraulic accumulator. The diesel engine remains running to provide for the auxiliary loads. During braking, the diesel engine is also decoupled and the hydrostatic pump transfers the braking energy into the accumulator.

The equipment employed to configure the parallel arrangement must be sized to provide the optimum energy-operational-efficiency to torque-requirement relationship. That is, the transmission gear ratio must be selected to provide the best engine on/off duty cycle over a range of working pressures to provide the required torque at the drive wheels.

The parallel arrangement is controlled by a microprocessor which initiates the appropriate engine duty cycle for the selected transmission gear ratio operation, based upon driver input and drive axle requirements.

To operate in the bypass mode, in which the wheels are driven exclusively by the engine, the transit vehicle operator must de-clutch the hydrostatic pump/motor from the main drive shaft.

There are two parallel hydraulic accumulator development systems, both from Europe and both more advanced and documented than the two serial systems previously mentioned. The first system was developed by the Technical University of Denmark, the second in Germany, principally by M.A.N.

The Technical University of Denmark's hydraulic/regenerative power system was designed for eventual retrofit applications to existing bus propulsion designs. It was installed in a Leyland bus in 1980. The total auxiliary system weighs about 1200 pounds. The accumulator tanks are made of steel. The high pressure (2000 to 4300 psi) tanks have a capacity of 28 gallons while the low pressure (about 40 psi) reservoir tanks hold about 22 gallons. This system has a reportedly simple design and is built from commonly available equipment. Results of passenger service demonstrations in Copenhagen indicate fuel savings of over 30 percent. Additional prototype vehicles are planned. Tri-County Metropolitan Transportation District is planning on demonstrating and testing this design, or an updated design of this concept, in the near future.

Efforts on a second type of hydraulic accumulator system using a parallel design configuration started at the Technical University of Berlin. Other organizations, including M.A.N., eventually participated in the work. A propulsion configuration designed and built by the Technical University of Berlin is shown in Figure 26.

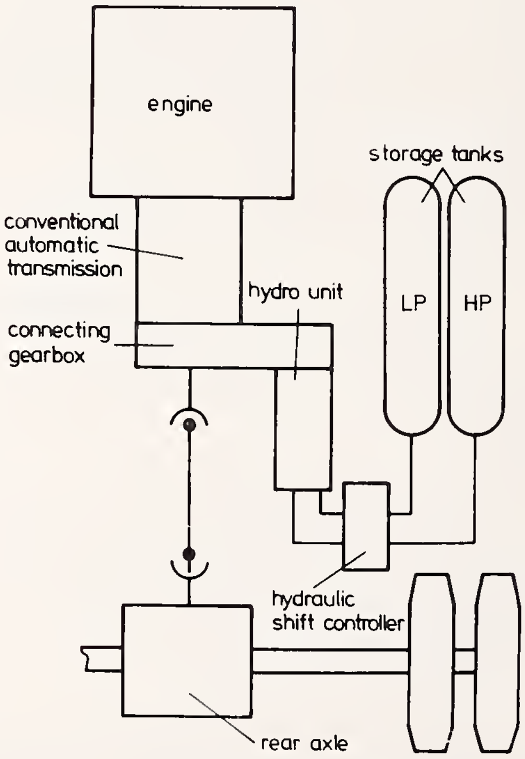

FIGURE 26. LAYOUT OF HYDROBUS I

The vehicle using this drive system was called Hydrobus I. The Hydrobus I uses a conventional diesel engine transmission but is fitted with a hydraulic unit connected to the prop shaft to operate the mechanical energy storage system. The auxiliary propulsion unit added over 2000 pounds to the bus.

In the late 1970s, M.A.N., in conjunction with the Technical University of Berlin and other public and private sector organizations, developed a new system called Hydrobus II. This advanced design uses a continuously variable transmission and hydraulic units (pumps and motor) which are connected to the drive system for both power splitting and for handling the oil to and from high-pressure storage tanks. Figure 27 shows the layout of this design.

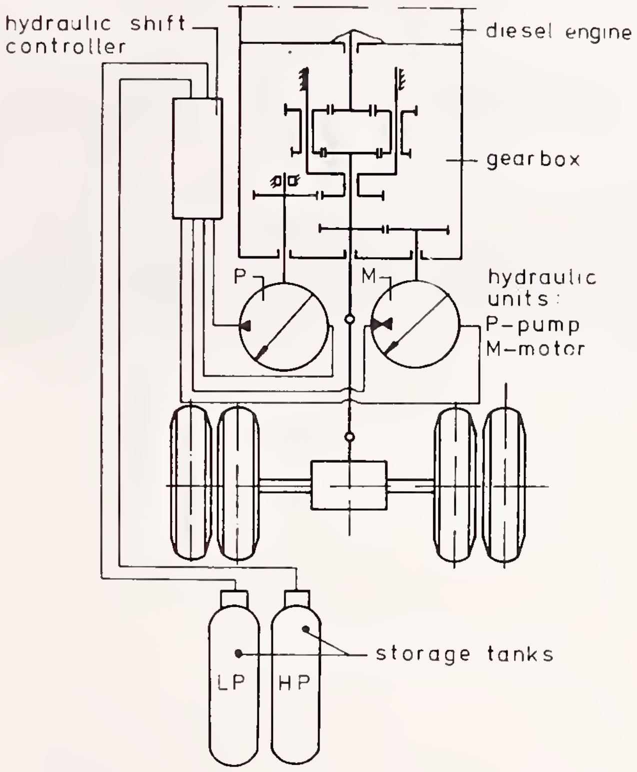

FIGURE 27. LAYOUT OF HYDROBUS II

The original design of Hydrobus II used four steel accumulator tanks (Figure 28) each holding about 1000 pounds of hydraulic fluid operating up to a maximum pressure of 4800 psi. The energy capacity of the system is reportedly sufficient to store the kinetic energy of a transit bus as it decelerates from speeds of over 30 mph to 0 mph. M.A.N. estimates some increase in acceleration. It is reported that in tests in city traffic, Hydrobus I achieved a 20% savings in fuel while Hydrobus II achieved up to 29% improvement.

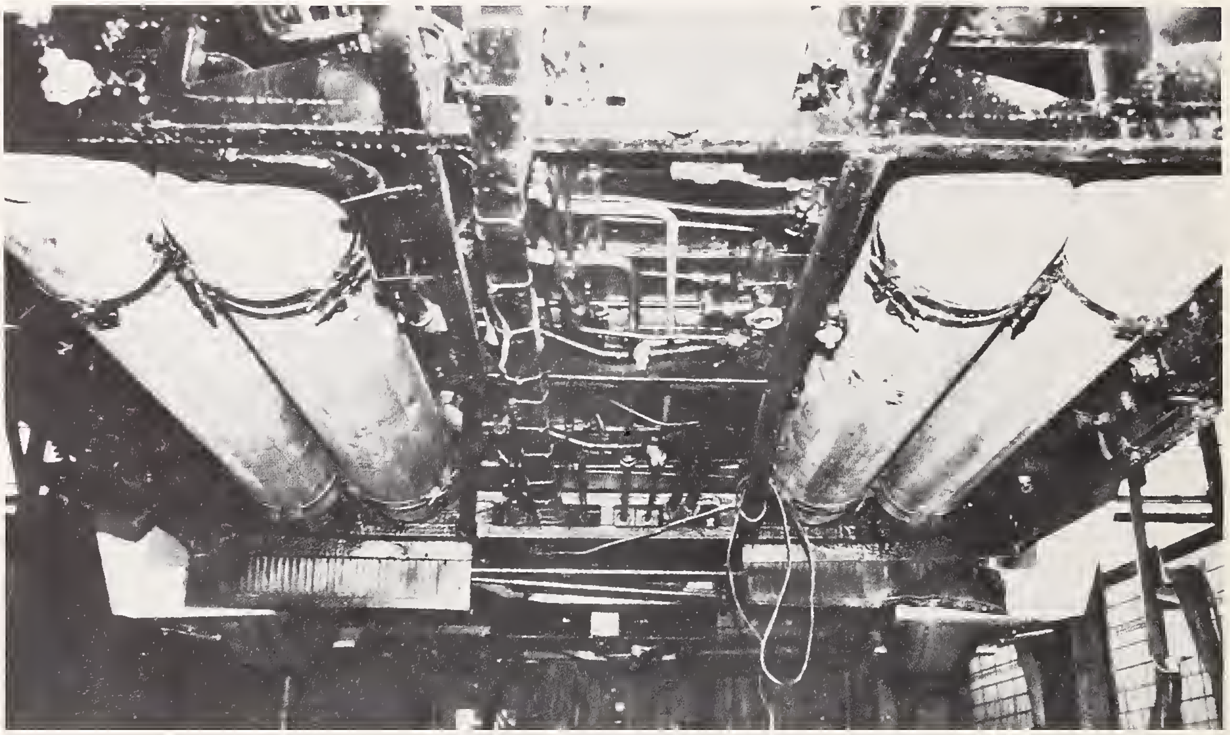

FIGURE 28. ARRANGEMENT OF STEEL ACCUMULATOR TANKS IN HYDROBUS II

4. SUMMARY FINDINGS

Bus hybrid propulsion technology generally includes equipment designs having two independent means of moving the vehicle, and designs that merely provide a second energy source. A useful categorization of hybrid propulsion technologies is:

a. Dual hybrid - two systems of approximately equal performance;

b. Auxiliary hybrid - the second system is designed as a back-up with limited performance capabilities; and

c. Load-leveling hybrid - the second system is used to assist during acceleration only and generally involves regenerative braking.

A significant portion of the hybrid propulsion or energy equipment research conducted worldwide has focused on trolley bus applications. In addition, much of the hybrid propulsion research has been conducted in Europe. Major foreign contributors to the development of this technology include: Mercedes and M.A.N. in Germany; Renault in France; Fiat in Italy; and Volvo in Sweden.

With the exception of UMTA-sponsored research activities in areas such as auxiliary back-up power sources and dual-power systems for trolley buses, stored hydraulic energy systems and inductive couplings, little activity has occurred in the U.S. transit community on deploying hybrid propulsion technology. (Table 2, entitled "Summary of Hybrid Propulsion Technology" and located in Section 3.1, provides a useful reference of the general characteristics of a variety of worldwide hybrid systems.)

Information on hybrid technology is difficult to obtain. This is due to claims of proprietary status by manufacturers and communication problems with foreign equipment suppliers. In addition, it is difficult to determine whether manufacturer claims truly represent actual, realistic test performance. In certain cases, the information that is available is either theoretical or laboratory data, or too limited in quantity to allow useful conclusions to be drawn. Often, there is no clear distinction between test data and revenue service data, nor between experimental and production vehicles.

It is clear that more information is needed concerning the performance of vehicles using hybrid propulsion systems under realistic conditions. Equally important is the need for more information on costs - initial, operating and maintenance - so that informed judgments on the usefulness of this technology in various applications can be made.

Research, development and testing conducted in this country should be coordinated under a plan which assesses future bus transit needs, alternatives, potential impacts and potential markets.

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