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Computer Simulations and Literature Survey of Continuously Variable Transmissions for Use in Buses

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Final Report

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16. Abstract

A literature survey considers several examples of continuously variable transmissions (CVT's) in buses, both with and without flywheel energy storage, and finds a predicted energy savings of 10 to 32 percent. The analysis focuses on the use of a CVT alone, without regenerative braking. Computer simulations are made to compute the fuel use of a bus with two different CVT's--one with a ratio range of 6, and the other of an infinite ratio range. For the former, assuming an efficiency of 85 percent, a fuel savings of 12 to 22 percent is predicted, depending upon the driving cycle. It is shown that a substantial part of this saving arises from the simple fact that the accessories operate at a lower speed. For this reason, a separte study of accessory speed control has been conducted, yielding a predicted fuel saving of as high as 17 percent. It is concluded that such accessory speed control may represent an attractive way to reduce fuel consumption. In comparison with the CVT, the concept is more compatible with present bus technology.

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PREFACE

Numerous studies have been conducted on the concept of flywheel energy storage for buses. Under U.S. Department of Transportation (DOT) funding, the General Electric and the Garrett AiResearch Corporation have had parallel contracts to design and build all the necessary prototype components of these systems for laboratory testing. Flywheel systems require a continuously variable transmission (CVT) of some type to transmit power between the flywheel and the drive wheels. However, a CVT can provide some fuel economy benefit and without an energy-storing flywheel, the focus of the present study.

This study has been sponsored by James Campbell, Office of Bus and Paratransit Technology, Urban Mass Transportation Administration (DOT).

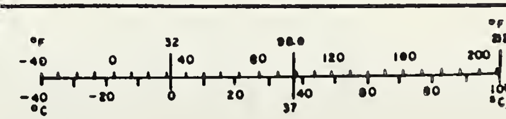
METRIC CONVERSION FACTORS

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	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

This computer study and literature review is intended to provide insight into the potential applicability of continuously variable transmissions (CVT's) to buses. It has been suggested that such transmissions may be of interest for two reasons:

1) Simple substitution of a CVT in the place of a conventional transmission may offer fuel savings by allowing the engine to operate at its most efficient speed.

2) The combination of a CVT and a flywheel allows regenerative braking, in which the vehicle kinetic energy during deceleration is captured for later re-use.

The amount of literature in this area is vast. An existing survey of continuously variable transmissions and related subjects[1*] contains over 200 sources. A recent bibliography on the subject of flywheels[2] lists over 400 references.

In order to reduce the field to be surveyed to a managable level, it was decided to confine it to those transmission concepts which are most applicable to buses as opposed to cars. Furthermore, it was decided that a relatively intensive survey of a limited number of sources would give a clearer picture of the present and future state of technology than would a broad survey of all the references available.

For reasons given in Section 4, belt drives and traction drives were not considered to be likely candidates for buses and, hence, sources dealing exclusively with such concepts were not included in the survey. References 3 through 5 are studies sponsored by the U.S. DOT in the subject of hybrid buses. Reference 6 is a broader study conducted at the University of Wisconsin on flywheel vehicles in general. The U.S. Army conducted an

*Superscripts refer to references discussed in the Appendix.

early study of buses using wayside recharging.[7] Two additional studies [8,11] are concerned with electric passenger cars having electric transmissions which might be scaled up to a size applicable to buses. References 9 and 10 are both concerned with computer simulations of hybrid buses and their potential for fuel savings. Scaling factors for electric motors are discussed in Reference 12. An interesting study by General Motors[13] compares the projected performance of CVT's with alternative advanced automatic transmissions. Finally, a report from the German manufacturer MAN[14] gives experimental data from their "brake-energy recovery" drive system for buses.

In order to lend some perspective to the claims for potential improvement in these various sources, calculations for a hypothetical CVT having a constant value of efficiency were made using an existing simulation program. Such calculations give upper and lower bounds to the possible energy savings.

2. SUMMARY AND CONCLUSIONS

Many of the references cited contain some kind of investigation to determine the most appropriate types of transmission for buses. Surveys which encompass most types of CVT's (including traction and belt drives) are included in References 3, 5, 6, and 7, all of which concluded that the hydraulic and electric concepts are most appropriate for buses. (For purposes of this discussion, the addition of a parallel mechanical power flow path does not alter the type of transmission, i.e., electromechanical is the same type as electric). The surveys found in References 4 and 10 are limited from the start to electric and hydraulic, implying that these investigators reached the same conclusion a priori. Some of the fundamental physical reasons why traction and belt drives do not look promising for buses are given in Section 4.

2.1 FUEL ECONOMY

Table 1 contains predicted improvements in the fuel economy of buses using CVT's. An earlier TSC study[1] is the only source which reports on the CVT alone, without the use of regenerative braking, for use on buses. However, References 5 and 13 both report on CVT's without energy storage for use on cars, and predict energy savings of 15 and 16 percent, respectively, in substantive agreement with Reference 1. There is, however, one important caveat as reported in Reference 13; it may be possible to obtain similar fuel economy gains through improvements to conventional transmissions.

2.2 REGENERATIVE BRAKING

If regenerative braking is included, predicted fuel savings range from 12 percent to 32 percent, with the amount of improvement depending heavily on the driving cycle.

The computer study which was undertaken as part of the present report focused on the CVT alone and did not consider the

TABLE 1. SURVEY RESULTS - PREDICTED IMPROVEMENT IN BUS FUEL ECONOMY USING A CONTINUOUSLY VARIABLE TRANSMISSION

REFERENCE	ORGANIZATION	TRANSMISSION	DRIVE CYCLE	STOPS/ MILE	REGENERATIVE BRAKING	FUEL CONSUMPTION DECREASE (PERCENT)
1	TSC	Sundstrand Hydrostatic	UMTA-B	5	NO	17
3	Garrett-AiResearch	Electric	UMTA-C	5	YES	12
10	Technical Univ. of Denmark	Hydrostatic (Bent-Axis)	Typical Urban	Not Given	YES	32
14	MAN	Hydrostatic	Typical Urban	Not Given	YES	15-25

additional improvement which would be available through the use of regenerative braking. As can be seen from the literature survey, the regenerative aspect has already been studied in some detail.

The results of these simulations are shown in Table 2. Since this was a general study, calculations were not made for any particular CVT, but, instead, two values of average efficiency were assumed, namely 85 percent and 100 percent, which were constant throughout the ratio range. These two values represent the upper and lower extremes of interest, since it is impossible to exceed 100 percent efficiency, and a CVT with 85 percent efficiency may be considered typical of the current state of the art.

2.3 RATIO RANGE

Besides efficiency, the other parameter of major interest is the ratio range of the CVT. For any given input rpm, the output of the CVT can vary from a certain maximum speed to a minimum speed. The ratio range is defined as the ratio of these two speeds. If the minimum output speed is zero, the ratio range is infinite. A transmission with this property is known as an IVT (Infinitely Variable Transmission). Hydraulic and electric types of transmission usually have this property. However, an IVT with a constant efficiency throughout its range has yet to be invented. Such a device could generate infinite torque at zero output speed and seems most unlikely. Under the assumption of constant efficiency, it is more realistic to perform calculations for a CVT with a specified range, although the IVT still represents an interesting limiting case.

As shown in Table 2, substantial improvements are theoretically available through the use of an IVT, with up to a 33 percent fuel savings being possible under some driving cycles. Driving cycles used in the simulations are shown in Figures 1 and 2. Similar calculations for the case of a "perfect" torque converter (having 100 percent efficiency) do not show comparable gains. This shows

TABLE 2. SIMULATION RESULTS -- PERCENT DECREASE IN BUS FUEL CONSUMPTION WITHOUT REGENERATIVE BRAKING

Drive Cycle	Stops/ Mile	TC-490 Torque Converter	100% Eff. Torque Converter	CSAD	85% Eff. CVT 6:1 Range	85% Eff. IVT	100% Eff. IVT
UMTA-C	5	Baseline	7	14	17	22	32
CBD	7	Baseline	7	11	19	24	33
Arterial	2	Baseline	4	14	12	15	26
Commuter	0.25	Baseline	1	17	22	23	33

Bus Weight = 30,000 lb

Engine = DDA 6V92TA

Accessories Included

Baseline Gearbox Data:

1st Gear = 2.067

2nd Gear = 1.401

3rd Gear = 1.000.

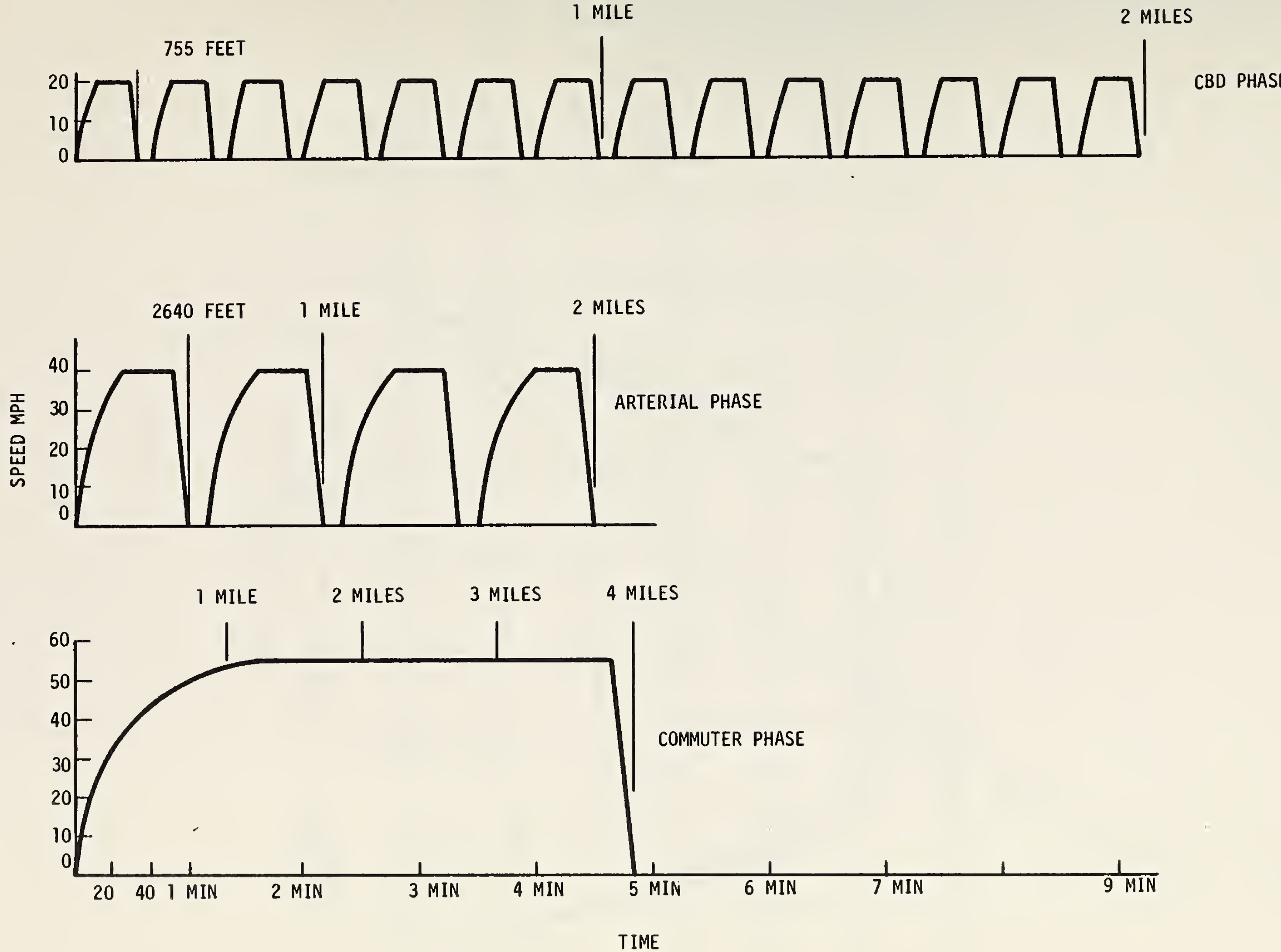

FIGURE 1. TRANSIT COACH OPERATING PROFILE DUTY CYCLE

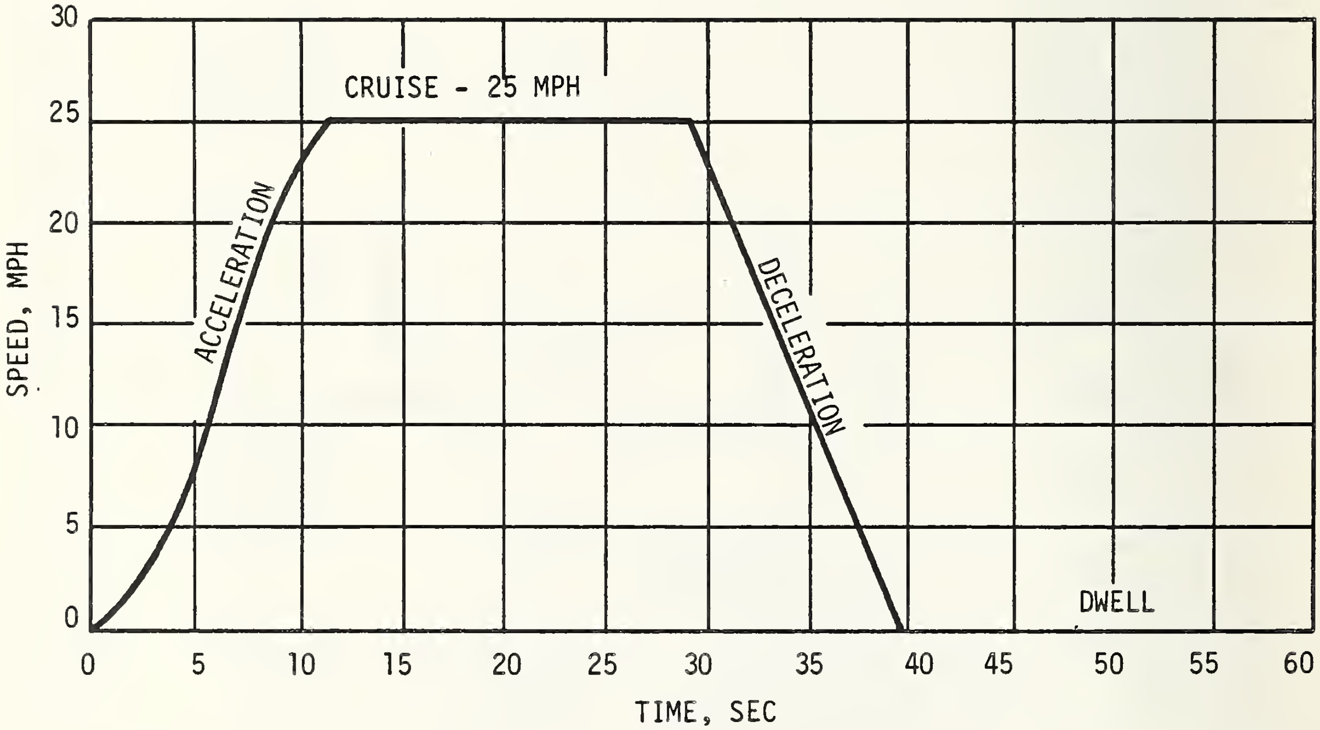

FIGURE 2. UMTA DRIVING CYCLE C

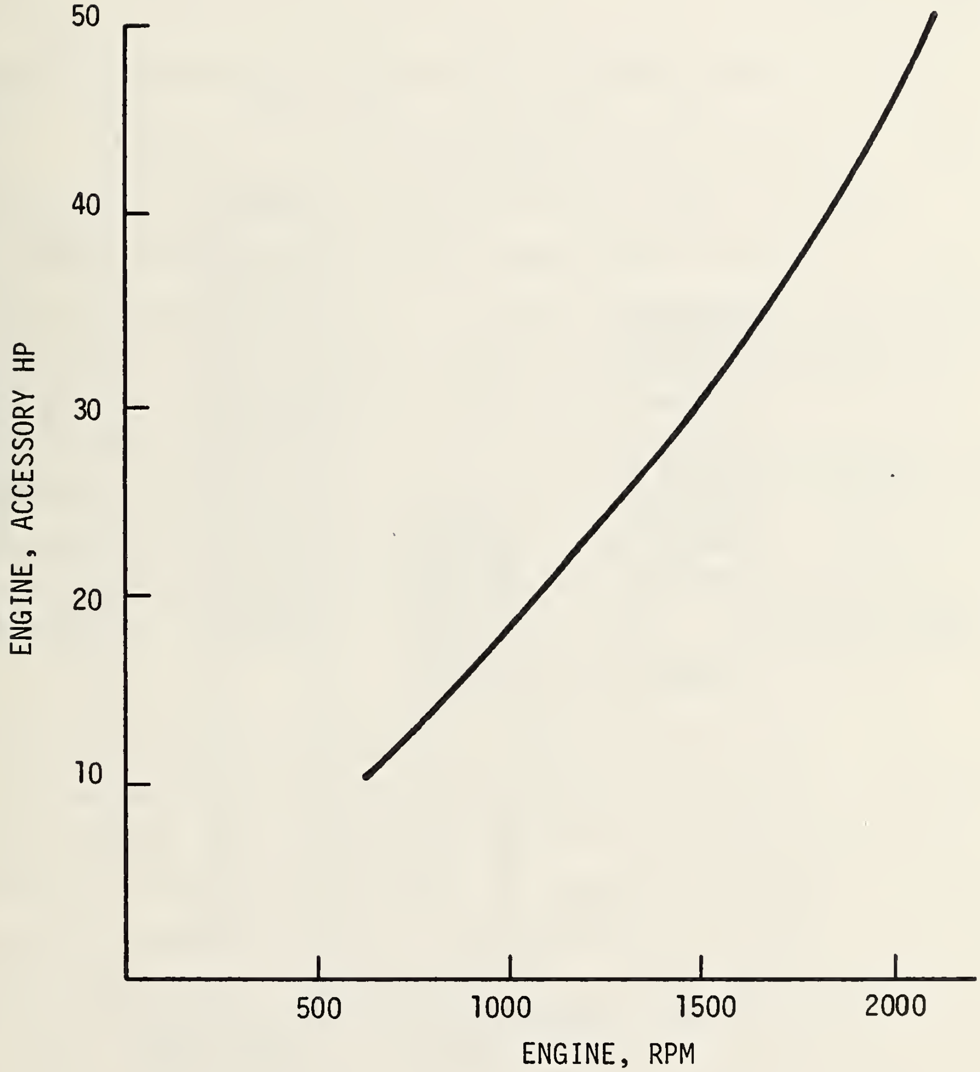

FIGURE 3. ACCESSORY LOAD AS A FUNCTION OF SPEED, ASSUMING AIR CONDITIONER AND FAN OPERATE AT MAXIMUM CAPACITY

that most of the fuel economy gain of the IVT is not due to reduced losses within the transmission itself but, instead, is because the engine and accessories can operate at a lower speed.

2.4 ACCESSORY LOAD

The accessory load, shown in Figure 3, corresponds to air conditioning plus the usual remaining items (fans, lights, etc.). A simple hand calculation was performed of the propshaft horsepower, accessory load, and transmission losses at 20 mph, for the IVT with 100 percent efficiency and for the conventional city bus. The result is shown in Figure 4. At this speed, the accessories consume about half the total energy. It is apparent that a major reason for the decreased fuel consumption of the IVT is simply the reduced accessory load because the engine can operate at a reduced speed. However, this same result can be accomplished through a Constant Speed Accessory Drive (CSAD), which amounts to a small CVT inserted between the engine and the accessories. The CSAD is certainly not a new concept; such drives are currently under study for use in automobiles.

Simulations were performed for a standard bus with a conventional transmission having a CSAD which could maintain the accessory load at a constant level of 10.5 horsepower for all engine speeds. These results are shown in Figure 5 and also in Table 2 for the four drive cycles under consideration. As can be seen, a major portion of the fuel savings which are apparently available from the IVT can be obtained from the much simpler and more conventional CSAD. Of particular note is the comparison for the arterial drive cycle, which shows that the IVT has no advantage over the CSAD. This is because the transmission used in the city bus being simulated is quite well-suited to the 40 mph cruise speed of this particular drive cycle; so, the potential savings from the IVT are relatively small.

2.5 DRIVE CYCLE

The values shown in Figure 5 give an upper bound for the potential energy savings from the CSAD, since it has been assumed

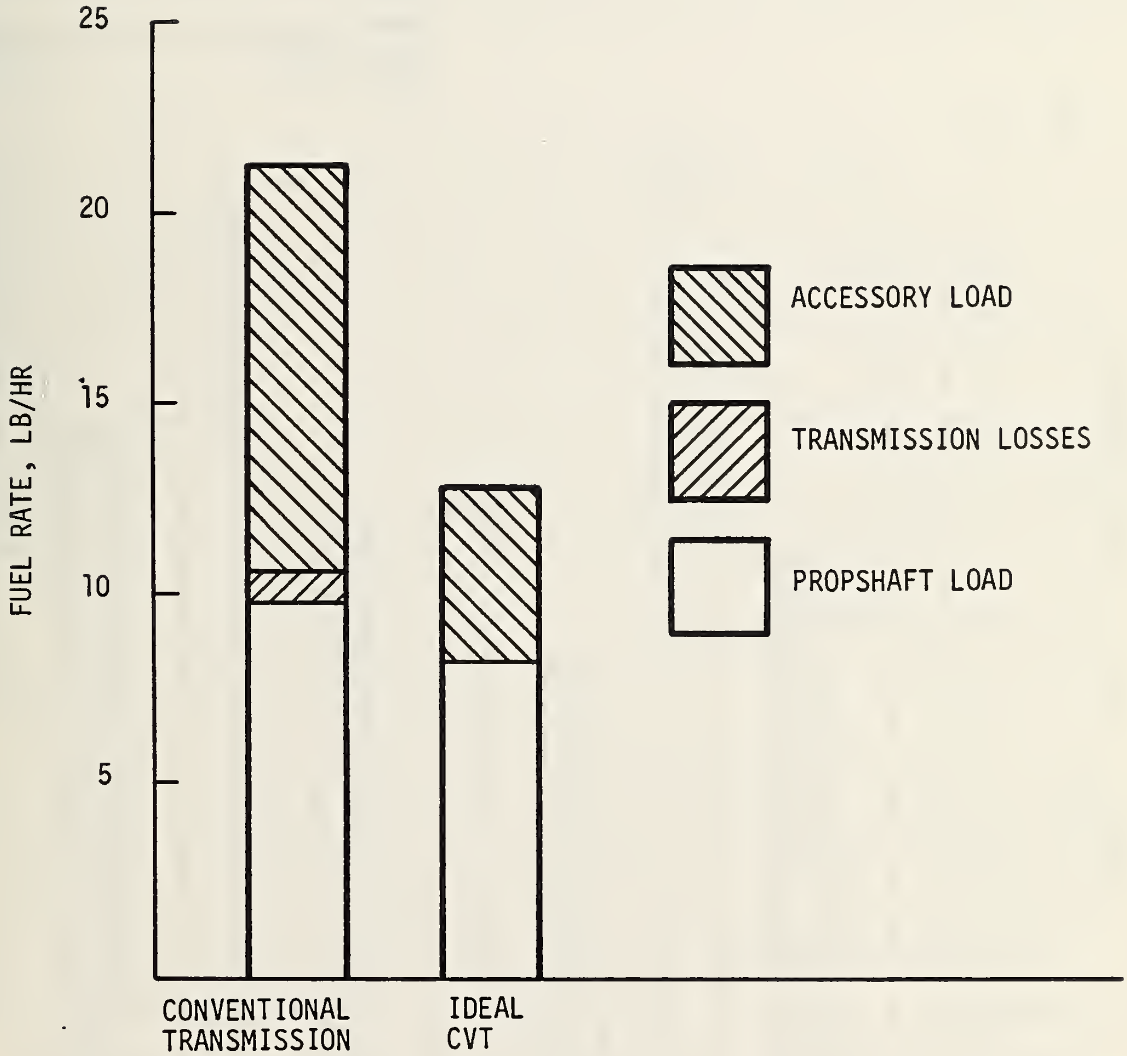

FIGURE 4. FUEL CONSUMPTION AT A STEADY 20 MPH, ASSUMING AIR CONDITIONER AND FAN OPERATE AT MAXIMUM CAPACITY FOR GIVEN SPEED

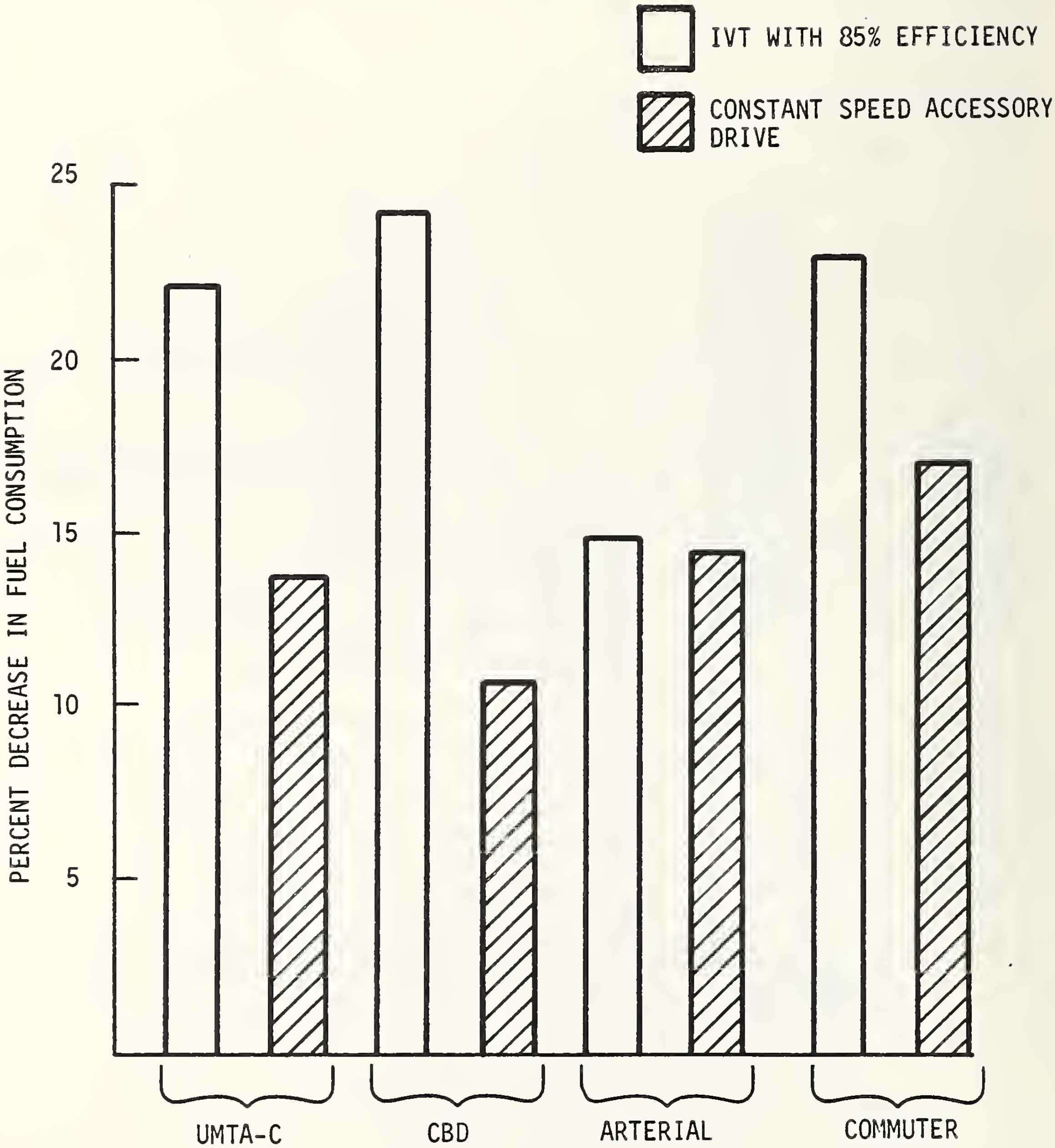

FIGURE 5. COMPARISON OF FUEL SAVING--IVT VERSUS CONSTANT SPEED ACCESSORY DRIVE. ASSUMES AIR CONDITIONER AND FAN OPERATE AT MAXIMUM CAPACITY FOR GIVEN SPEED

that the accessories always operate at their maximum capacity for the given engine speed. The actual savings may be less than this. At high engine speeds the air conditioner compressor and the engine cooling fan may be cycled on and off, depending on the outside air temperature and the details of the thermostatic controls, so that the accessory load may be less than that shown in Figure 3.

The results of the UMTA-C drive cycle are perhaps the most pertinent for evaluating the effectiveness of the CVT, since simulations using this particular cycle with 5 stops per mile predict fuel consumption which is very close to that actually obtained under typical transit use. Even though a "realistic" CVT with 85 percent efficiency and a 6 to 1 ratio range would give a 17 percent decrease in fuel consumption, this should be compared to the improvement available from the CSAD, which may be as large as 14 percent. In other words, the additional improvement over the CSAD may not be enough to justify the additional expense for the CVT. On the other hand, if a CVT with a significantly greater ratio range and/or efficiency could be developed, the potential improvement might be worthwhile.

It should also be pointed out that the very large improvements which are shown for the commuter cycle are mostly because the city bus transmission is inappropriate for the 55 mph cruise portion of this cycle. Fuel savings which are similar to those shown for the 85 percent efficient CVT could be obtained by simply adding a fourth gear or an overdrive to this transmission.

The overall conclusion to be drawn is that there are many available methods for improving the fuel economy of buses. The CVT alone does not offer significant improvement over that available from more conventional approaches such as constant speed accessory drives or the addition of overdrive.

The computer study, Section 3, was not concerned with determining the desirability of a CVT coupled with an energy storage device. However, the material in the Appendix (literature survey) indicates that such a combination is indeed promising.

3. ANALYSIS - METHOD OF CALCULATION

The VEHSIM (Vehicle Simulation) computer program has been developed at the Transportation Systems Center (TSC) of the U.S. DOT in order to compute fuel consumption for vehicles under various driving cycles. Power required, engine speed, total drag, transmission losses, etc., can be computed on a step-by-step basis for each individual time interval until the specified cycle is completed.

A recent modification of this program, HEVSIM (Heavy Vehicle Simulation), allows similar computations to be made for trucks and buses. One of the most useful outputs of this program is a histogram which indicates the total time spent within each range of engine rpm and torque level. Once such a histogram is available, the computation of fuel consumption is simply a matter of adding the fuel used in each part of the engine map.

In order to calculate fuel consumption for the IVT, a new type of histogram was created based on propshaft horsepower. That is, this new histogram gives the total time spent within each range of propshaft speed and torque level. The product of the two (speed times torque) gives the horsepower level. Knowing the horsepower, the fuel consumption rate at the optimal engine speed can be found from the engine map.

In the actual computation of fuel consumption for the CVT, it was not necessary to use the engine map for each individual increment. Instead, a new graph was created giving fuel rate as a function of horsepower at the optimal speed. This is called the "optimal engine line" (Figure 6). Since the engine speed at each point on this line is known, it is possible to calculate the accessory horsepower requirements. The difference between the two gives the net horsepower which is available to drive the propshaft, assuming no power losses in the CVT.

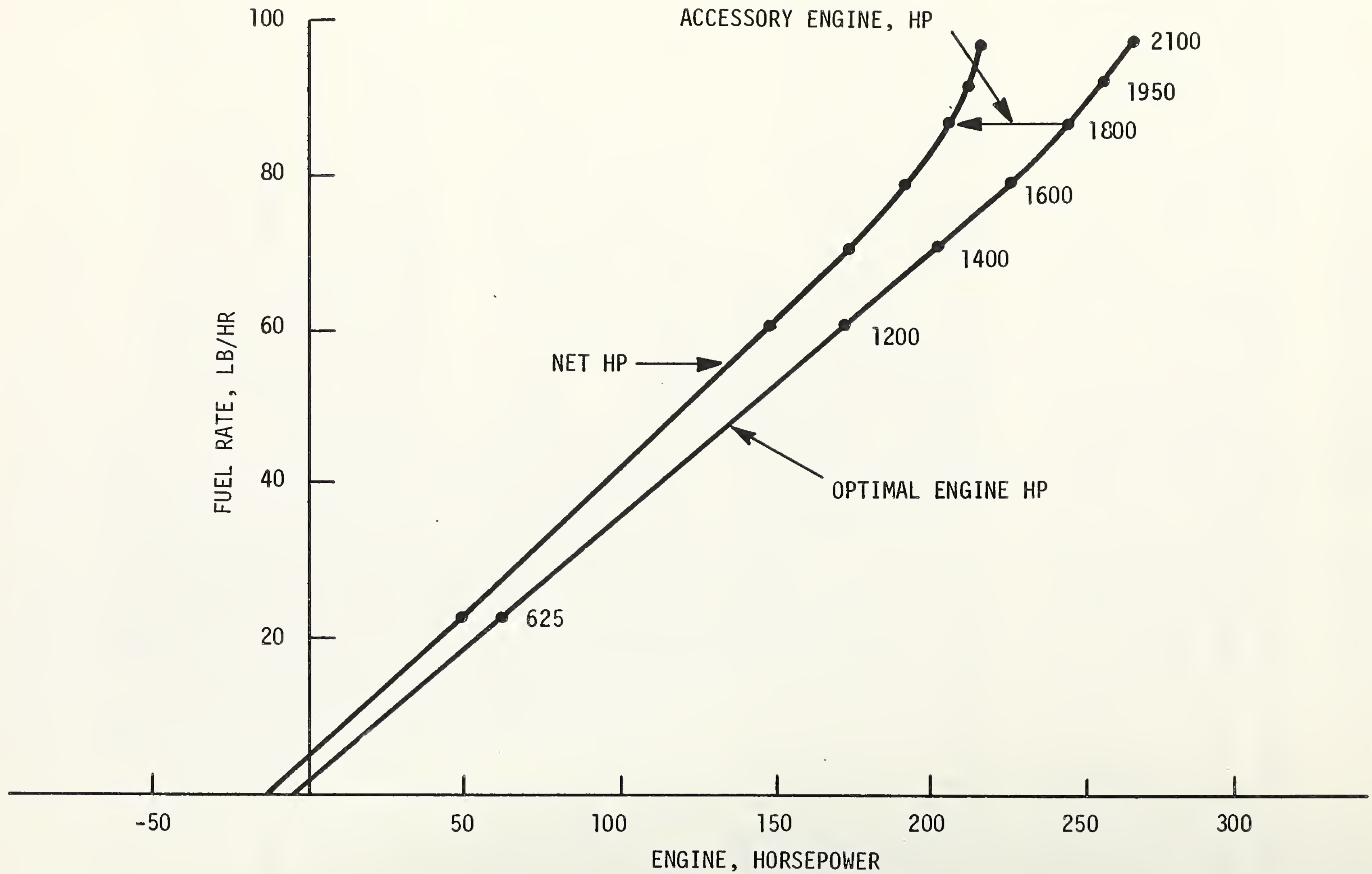

FIGURE 6. FUEL CONSUMPTION AT THE OPTIMAL RPM FOR THE GENERAL MOTORS 6V92TA DIESEL ENGINE WITH TYPICAL BUS ACCESSORIES

Thus, starting with the histogram, computation of the fuel used is extremely simple. Given propshaft horsepower, the fuel rate is found from the "net horsepower" line. Total fuel used is found by summing the fuel used in each portion of the histogram.

It is worth noting that the most straightforward calculation of fuel used with an IVT would not actually require a simulation. Propshaft horsepower is directly related to road load (drag plus accelerating force) and could be calculated directly from any given drive cycle. However, for purposes of calculating fuel consumption relative to that of a conventional transmission, the histogram method outlined above has certain advantages:

1) It allows a direct comparison on the basis of equal performance.

2) Calculations of tire losses, aerodynamic drag, and rear axles losses are performed in an identical manner for both types of transmission. This allows a more accurate evaluation of the differences in fuel consumption.

For the CVT, as opposed to the IVT, the simulation used a conventional torque converter from 0 to 5 mph. At 5 mph, the torque converter was locked up, and a CVT was inserted whose lower transmission ratio allowed the engine to operate at the optimal speed for the required horsepower. As it turned out, the engine idle speed (with throttle angle increased) was adequate to provide an acceleration equal to that available from the conventional transmission. The upper transmission ratio for the CVT was chosen to allow the bus to cruise at 55 mph, again with the engine at the optimal speed for providing the necessary power. A total ratio range (upper ÷ lower) of 6 was obtained from this procedure. Note that the same transmission is assumed for all of the drive cycles shown in Table 2. If a CVT were to be chosen to be specifically tailored to the CBD cycle, for example, a much smaller ratio range could be utilized.

In the actual calculation, the transition from conventional transmission to CVT was not actually simulated. Instead, new histograms were created which excluded all contributions for which the bus velocity was less than 5 mph. By comparing results from these histograms to those of the previous histograms, fuel consumption for the torque-converter/CVT combination could readily be computed.

4. LITERATURE SURVEY

CLASSES OF CVT'S CONSIDERED

The technological insight which can be gained from the present survey can be greatly enhanced if certain issues are first understood. One of these is the concept of scaling, which has direct bearing on the question of how we distinguish between those transmissions which are applicable to cars and those which are applicable to buses. The question becomes "which concepts work well at small sizes and which show more favorable characteristics as size is increased?"

At this point, it is useful to introduce a distinction between volume phenomena, surface phenomena, and edge phenomena, which occur in three, two, and one dimension respectively. A good example of a device which operates on a volume phenomena is a hydraulic pump, whose output is proportional to its displacement, i.e., the cylinder volume. One example of a device which operates on a surface phenomena (which we call a surface device) is a belt drive, in which power is transmitted via the surface contact between the belt and the sheave. Some insight may be gained by asking "what happens if each linear dimension of a device is doubled?" With a volume device the power handling capability is multiplied by a factor of eight, directly proportional to the increase in weight. However, the losses of the device are often surface phenomena, such as friction, or edge phenomena, such as leakage around the seals, which are only multiplied by factors of four and two respectively. Thus, the losses increase to a lesser extent than the output, so that the efficiency increases as the size increases. This is what we mean when we say that <u>volume devices scale well</u>, i.e., things get better as the size increases.

To pursue this argument with a surface device, if we double the dimensions of a belt drive the power handling capability only increases by a factor of four, so that we end up with half the power per unit weight. In order to prevent the transmission from growing unreasonably in size, the designer is forced to put a plurality of such devices in parallel. With two devices, for example, we have both twice the capability and twice the weight, so that the power per unit weight is almost the same. We say "almost" because invariably it is necessary to add some additional mechanism in order to be sure that the load is shared equally. Not only will this increase the weight, but it will also create an additional penalty in terms of complexity. To summarize, <u>surface devices do not scale well</u>.

A large variety of transmissions fall within the category of traction devices, which are characterized by a continuous slip between two hardened surfaces. Continuously variable traction devices have been used for years in stationary industrial applications, particularly for low power ranges. The fact that they are surface devices helps explain why the transition to higher power ratings and power densitites necessary for vehicular applications has been so difficult. Another problem is the difficulty in making rapid changes in transmission ratio.

Energy storage devices generally utilize volume phenomena, so they all have characteristic energy densities, expressed in terms of watt-hours per kilogram, which are more or less independent of size. If the same were true of transmission concepts we could simply decide what concept looks most attractive in terms of power to weight ratio, and devices using this one concept could be scaled up or down to meet the needs of all vehicles from small cars to large buses. However, as we have seen, for many transmission concepts, the power density is not constant, so that different concepts look better at different scales.

It is not possible to classify electric motors as either volume devices or surface devices, since some types of motors show improved characteristics at large scales whereas others become more attractive at small scales. It is worth noting that the basic force-producing phenomena in such machines is the electromagnetic field which occurs in the volume between the stationary part and the rotating part. For a given rotational speed, the power density of the machine is limited by the energy density of this field, which in turn is proportional to the square of the flux density. The flux density is essentially independent of scale, so that the type of electric motor which is commonly found in large sizes is basically a volume device. However, for reasons which are beyond the scope of this survey, electric machinery shows greater improvement with increasing scale than other categories of volume devices such as hydraulic pumps or mechanical transmissions. Some of the reasons behind this are given in Reference 12.

The recent technological trend in electric drives for CVT's has been toward increasing use of semiconductor devices. This throws some confusion into the picture since these are surface devices, i.e. the actual flow of power (in the form of electrons) takes place across a p-n surface junction. As such, we can expect that they do not scale well, and, indeed, the standard technique for building large power conditioning units is to put a number of devices in parallel, together with some means for insuring that the load is shared equally. Although the power to weight ratio of solid state power conditioners can be kept reasonably constant as the scale is increased, there are no economies of scale, that is, the cost per kilowatt remains constant, unlike the motor cost per kilowatt which decreases gratifyingly at the larger sizes. In spite of the enormous strides in the power handling capability of semiconductor devices over the last several years, cost is still a major problem.

To reiterate the major point of this discussion, surface devices work well at small scales, and volume devices work well at larger scales. Because this literature review is focused on buses, it was decided to concentrate on volume devices such as hydraulic drives and electric drives. The surface devices, such as variable-sheave belt drives, are now undergoing experimentation (Fiat) for light passenger cars, but their application for heavier vehicles with high torque requirements seems most uncertain. Therefore, it was decided to exclude surface devices from the literature review.

Another important background concept is the notion of parallel power flow paths, implying either split-torque or regenerative gearing.* In what follows, we use the term "basic element" to denote the part of the transmission which actually provides the continuous variation. For the most common CVT's, this consists of either a variable sheave, a traction drive, or a hydrostatic drive.

By the use of epicyclic gearing (i.e., a planetary gearset or a differential), the ratio range of a CVT may be contracted or expanded. Contracting the ratio is accomplished through what is known as a "split torque" arrangement, whereas expanding the ratio is known as regenerative gearing. With the former, a substantial portion of the power bypasses the basic CVT element, going directly from input to output without significant mechanical losses. This has two advantages: the basic element can be smaller and the overall efficiency is higher than that of the basic element. Hence, the split torque arrangement is suitable with a basic element which has a wide range and a low efficiency, such as a hydrostatic motor-pump combination. Generally, when a split-torque arrangement is used, the required ratio range is obtained through the use of conventional step-change gearing. The CVT provides continuous variation throughout a low range, for example, and then a conventional shift is made to a higher range, with the CVT being adjusted such that output at the beginning of the high range matches that at the end of the low range. Two examples of such an arrangement can be cited; the Orshanski Transmission, and the experimental vehicle built by Frank and Beachley.[6]

Regenerative gearing allows the ratio range to be expanded, thus, the need for shifting between ranges can be eliminated. The output can be made to shift continuously through zero and even into reverse if desired.

*The term "regenerative gearing" should not be confused with "regenerative braking," which is an entirely different concept.

With regenerative gearing, the power along one path flows in the opposite direction to that of the other; in other words, there is some recirculating power. This means that in some ranges the basic element has to carry more power than the input power. This has two disadvantages; the basic element must be made larger, and the efficiency of the transmission as a whole is less than that of the basic element.

The state of existing CVT technology can best be illustrated by imagining a large balloon with three lobes labeled "transmission size," "energy losses," and "limited ratio range." A designer can squeeze down on one or two lobes of the balloon, but whenever he does so a problem bulges out on the third lobe. By rearranging elements, it is always possible to show improvement in one or of the important characteristics, which helps explain why so many CVT configurations exist. However, for vehicular application none of the three lobes can be left unchecked.

APPENDIX

LITERATURE ABSTRACTS

Reference 1: State-of-the-Art Review Continuously Variable Ratio Transmissions

Report No. : DOT-TSC-UM-830-PM-78-6 II (Report on File at TSC)

Author : G. S. Larson and H. Zuckerberg

Org. : Transportation Systems Center

Date : June 1978

Abstract:

This study, in 2 volumes, assesses the near-term and long-term potential for improvement in urban bus fuel economy through use of Continuously Variable Ratio Transmissions (CVRT). In the first volume, various types of CVRTs are described, design objectives are identified, and the drives and developments of specific manufacturers are reviewed with a presentation of all performance data available. Recommendations are made towards a research and development program. Improvement in fuel economy of 20 to 30% is projected for buses in the urban environment through use of a CVRT, properly designed as an integrated element in the power drive train. In the second volume, an extensive Bibliography on CVRTs is presented.

Comments:

At the time of this writing, an updated version of this bibliography is being prepared at the Transportation Systems Center.

Reference 2: Flywheel for Energy Storage: A Review with Biliography

Report No. : ASME paper No. 76-DET-96

Authors : D.L. Hagen and A. G. Erdman

Org. : University of Minnesota

Date : September 1976

Abstract:

The use of flywheels is reviewed with an emphasis on energy storage applications. Use of the optimized homogeneous rotor, and the development of high strength composites and new rotor configurations have revolutionized flywheel design. The wide range of applications is discussed as a function of performance and economics. Theoretical and experimental work is reviewed, as well as design considerations of the rotor and related equipment. Current research and development activity is mentioned, along with an introduction to the literature. A comprehensive bibliography on flywheels over the last decade is given including representative references to related technological and economic areas.

Comments:

This review is quite comprehensive and covers all aspects of flywheels such as fatigue, materials, bearings, seals, etc.

Reference 3: Study of Flywheel Energy Storage
Report No. : UMTA-CA-06-0106-77-1 (Five Volumes)
Author : L. J. Lawson et al.
Org. : Garrett-AiResearch
Date : September 1977

Abstract:

An in-depth application study was conducted to determine the practicality and viability of flywheel propulsion for urban mass transit vehicles. The study began with a review of the U.S. transit properties requirements, which showed that the most suitable vehicle for deployment of flywheel propulsion is the full-size transit bus. Several propulsion concepts were hypothesized and subjected to comparative analysis with present diesel buses, trolley coaches, and battery buses in regard to performance and life-cycle economics. This screening resulted in the establishment of the following basic concepts that can provide various types of high quality transit service:

- Pure flywheel propelled bus
- Flywheel/diesel engine hybrid bus
- Flywheel-augmented trolley coach
- Flywheel/battery hybrid bus.

The design studies that were conducted for the four propulsion configurations then showed a high degree of commonality of components among the four concepts. Final life-cycle cost analyses showed all four concepts to be in a competitive range with present transit vehicles. Plans were made then for a Phase II development program that will result in the design, fabrication, and testing

of all four propulsion configurations in full-size buses within 36 months.

Comments:

All four of the above bus concepts are based on a common unit which Garrett calls a "flywheel machine." This is a sealed unit containing a flywheel and homopolar inductor motor, with electrical terminals for three-phase power. It operates much like a battery, i.e. during some periods power flows into the machine, and during other periods power flows out. It has a lower energy density than a battery, but a much greater power density.

The inductor rotor and the flywheel are contained in an evacuated chamber. For all concepts other than the diesel engine hybrid, nothing except magnetic flux penetrates the chamber walls--no shafts or even electrical leads. The coils for both the stator and the field are located outside the vacuum, where they can be oil-cooled.

At first glance the homopolar motor would appear to be a poor candidate for vehicular application, since by its very nature flux of only one polarity is used. This means that the available torque per unit weight of iron is only half what it would be in a bipolar machine. This drawback is more than compensated by the following attractive features:

1) The rotor can operate at extremely high speeds, since it is a solid piece of steel without coils.

2) Heat generated in the rotor is very low, which is essential for operation in an evacuated chamber.

Garrett feels the rotor heat can be dissipated out the rotor shaft and across the oil-lubricated bearings. This remains a technical uncertainty.

The diesel flywheel hybrid bus option which they considered deserves some comment. It is curious that they only considered a series transmission arrangement in which all the power flows through the flywheel machine. This incurs several disadvantages:

1) The flywheel housing cannot be hermetically sealed but must have a penetrating shaft with a rotating seal.

2) In order to start up the flywheel there must be a fluid coupling between it and the engine.

3) The overall drive is not as efficient as a parallel arrangement.

It is interesting that a later report by Garrett (Ref. 8) investigated a heat engine/flywheel hybrid automobile and concluded that a parallel configuration was the preferred choice. There is no obvious reason why the series configuration should be better for the bus and a parallel one should be better for the automobile. Since the present bus study had so many other configurations to consider (i.e. battery hybrid, pure flywheel, trolley) one suspects that Garrett didn't have the opportunity to consider multiple options for the heat engine hybrid and simply took the most obvious choice.

Finally, this study contains a rather interesting comparison between a flywheel storage system and a hydraulic system. For the urban drive cycle B the hydraulic system is lighter. However, the study specifications called for the bus to be able to climb a one-mile, five percent grade at 55 mph, which required a mammoth hydraulic accumulator weighing 11,000 lbs. For this requirement the flywheel system is considerably lighter. Garrett does state if this requirement were really essential it would make more sense to use a larger engine and a smaller accumulator. However, no design trade-offs are presented along these lines.

Reference 4: <u>A Study of Flywheel Energy Storage for Urban Vehicles: Phase I - Final Report, Preliminary Conceptual Design Studies</u>

Report No. : PB 282-929

Author : J. J. Fleck et al.

Org. : General Electric Corporate Research and Development

Date : September 1977

<u>Abstract</u>:

This report is one of a series which documents results of a program investigating the use of flywheel energy storage as applied to fixed-route,

multistop, rubber-tired, urban transit vehicles.

The complete program is planned as a multiyear project of four phases:

- Phase I - Preliminary Conceptual Design Studies
- Phase II - System Design, Fabrication, Test and Evaluation
- Phase III - Limited On-Road Demonstration
- Phase IV - Production and Development

This document is the final report for Phase I. It describes the studies which have resulted in selection of a preferred basic flywheel concept which can be applied to a variety of all-electric vehicles including an all-flywheel bus, a flywheel/trolley hybrid (line extender), and a flywheel/battery hybrid. The performance of the basic flywheel concept is described in some detail. This report also describes and contains results of life cycle cost studies for all-electric flywheel vehicles and conventional diesel, trolley, and battery vehicles.

It is concluded that flywheel energy storage is an extremely promising technique for reducing dependence upon petroleum fuels by urban transit buses; it also offers environmental improvement potentials. Life cycle costs for an all-flywheel system are estimated to be lower than those of existing trolley systems and very nearly the same as for diesel system.

Both of the flywheel hybrid systems show significant cost benefits compared to their conventional counterparts. Flywheel/trolley hybrid costs are nearly as low as the all-flywheel costs.

Installation and operation of flywheel propulsion systems in urban transit buses is considered to be feasible and practical. A program for hardware development is recommended.

Comments:

General Electric is the rival contractor to Garrett in the UMTA flywheel bus program. The studies of these two contractors were similar in most respects, the major difference being that GE does not report in their study on any flywheel hybrids with heat engines, nor do they report any comparison with hydraulic accumulators, as does Garrett.

This present GE conceptual design study ends up with a configuration which is very similar to that of Garrett, namely, a DC motor for traction and a homopolar inductor motor coupled to the flywheel. Along the way GE considered two very interesting split-torque transmission: (1) The hydromechanical split-torque, which they call the IVT (Infinitely Variable Transmission), (2) the electromechanical split-torque, which had been mentioned earlier as a possibility in Ref. 7. Curiously, GE does not supply any discussion of the relative merits of the electromechanical transmission, but simply elects not to chose it as one of the preferred options. This particular transmission is worthy of some detailed consideration, as illustrated by the fact that Garrett later used a transmission of this type in their "Near-Term Electric Vehicle" which is a battery/flywheel hybrid automobile funded by DOE (Ref. 11). It is possible that GE rejected this option because it involves a rotating shaft which penetrates the flywheel chamber, thus introducing the technical uncertainty of a rotating vacuum seal.

The hydromechanical transmission emerges as a very strong contender with the inductor/DC transmission. In fact, GE concludes that it is lighter, cheaper, has lower operating cost, and allows the bus to have a greater range. In spite of this, the all-electric transmission was chosen because it requires less development, has less noise, and was judged to be more reliable.

Finally, GE, like Garrett, recognizes some technical uncertainty on the issue of heat transfer from the evacuated chamber containing the flywheel and the inductor rotor. They propose filling the chamber with helium at a pressure of 0.01 atmospheres in order to allow some convective heat transfer. It is not clear whether GE or Garrett has the better concept on this issue.

Reference 5: Hybrid Vehicle Technology Constraints and Application Assessment Study

Report No. : DOT-TSC-OST-77-23

Author : D. E. Lapedes et al.

Org. : Aerospace Corporation

Date : November 1977

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.

The first volume constitutes a summary of the more important results of the study. The second volume contains the first four sections of the full report. It introduces the methods used in the study and the data base employed in simulation modeling of each vehicle powertrain. It also includes a technology review of powertrain components and various hybrid systems developed in recent years. The third volume contains five sections. Section 5 and 6 discuss the vehicle powertrain characteristics and the characteristics of the stationary generating plants. Section 7 describes physical and performance characteristics imposed on the hybrid vehicle. Section 8 describes computer programs developed for the analysis and Section 9 discusses results of the powertrain component sizing analysis. The last volume 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.

Comments:

The study concludes that the heat engine/flywheel hybrid has a greater overall efficiency, but the heat engine/battery hybrid has a greater potential for saving petroleum, since the battery can be recharged using energy which is derived from non-petroleum sources. Both series and parallel battery hybrids were considered, but the series configuration was examined in greatest detail. This was because this configuration showed its greatest advantage with short-range vehicles that can use frequent recharging, i.e., the very type of driving cycle for which the hybrid holds greatest promise. The parallel configuration is better for longer ranges.

The authors use what they call a "sophisticated simulation model" to predict fuel consumption and emissions. Various control schemes were considered and a scheme was chosen in which the output of the engine and battery (or flywheel) are blended together in a more or less continuous manner. The "on-off" control scheme was considered and rejected as too complex. Their arguments are very weak on this point as this particular scheme was not just simulated but actually implemented in the vehicle built at the University of Wiscousin (Ref. 6).

The report contains a brief examination of a Kevlar "superflywheel", which operates at extremely high rpm. It was concluded that significant advances in bearings and vacuum seals would be required.

Volume II contains a useful summary of hybrid systems which were actually demonstrated prior to 1976. Battery hybrid vehicles were built by GM, Mercedes-Benz, Petro-Electric Ltd., and Minicars, Inc. TRW build and tested a powertrain system on a dynamometer. Except for the Mercedes-Benz and GM systems, these vehicles were funded by EPA and were oriented to reducing emissions. None of them showed significant energy savings. A flywheel hybrid vehicle was built at the University of Aachen in Germany, and flywheel powertrain components were build and tested at Lockheed, Johns Hopkins University, and the University of Wisconsin. (The Wisconsin group installed their system on a vehicle after 1976. Ref. 6).

The Aerospace report, as the title might suggest, is a very cautious look at the technology of hybrid vehicles as it existed in 1976, using "off the shelf" components. They did not recommend using "superflywheels," and they based their calculations on the proven performance of DC traction motors rather than the lightweight AC motors which were later investigated by Garrett (Ref. 8). They avoided the "on-off" engine control scheme as being too complex. The report provides a good overall look at 1976 technology but does not claim to provide any advance in the state of the art.

Reference 6: Flywheel Energy Management Systems for Improving the Fuel Economy of Motor Vehicles

Report No. : DOT-RSPA-DPB-50/79/1

Author : N.H. Beachley and A. A. Frank

Org. : University of Wisconsin

Date : August 1979

Abstract:

The goals of the research program have been: (1) to develop, analyze and compare CVT designs to minimize the friction losses and weight of an integrated flywheel powerplant package, (2) to provide preliminary designs of flywheel propulsion systems for automobiles and minibuses, (3) to study the economic feasibility of production, (4) to obtain additional operational experience and experimental data on the research flywheel vehicle built at the University.

The experimental flywheel vehicle had demonstrated 32 mpg over the EPA-CVS Federal Urban Driving Cycle at an inertia weight of 2750 lb. Calculations based on experimental engine data indicate that federally-mandated emissions levels could be achieved with little degradation in fuel economy. The computer simulation programs developed have been verified by experiment.

With a full-sized engine to provide adequate hill-climbing ability, the flywheel need not be large, a capacity of about 1/3 hp-hr. being adequate for a 3,000 lb. car. Simulations show that a 75% fuel economy improvement over conventional cars is feasible with currently-available components. Results of component development in coming years may raise this figure. A flywheel hybrid powerplant is deemed practical in terms of control, size, and packaging. It should be economically attractive at gasoline prices above $1.00 per gallon.

Comments:

This reference represents one of the best sources of techniques for analyzing flywheel transmission systems. It is one of the few references which goes straight to the heart of the problem of coupling a flywheel to the rear wheels, and doesn't get bogged down in conceptual analyses of various configurations. The authors do a good job of increasing our understanding of the efficiency of variable transmissions, even though they feel compelled to point out that the necessary full-range data "is invariably unavailable."

The report is most directly concerned with automobiles, although the methods of analysis should be applicable to vehicles of all sizes. However, the authors warn that direct transfer of the data and conclusions to buses is not valid. They do reach the tentative conclusion that, of all the transmissions examined in their studies, the hydrostatic power-split looks most attractive for buses. One simulation is performed for minibuses which shows a 50% improvement in fuel economy for the EPA urban cycle.

Five different CVT concepts were evaluated (1) the hydrostatic power-split, (2) the electric power-split, (3) the toroidal traction drive, (4) the variable V-belt drive, and (5) a multi-speed gearbox with a controllable slipping clutch. Of these, the rubber V-belt gave the highest fuel economy when used in conjunction with a two-speed gearbox and a flywheel. However, the reliability of the V-belt may be a problem, and there is no existing V-belt which can handle the full power load. At the time this report was written, no information was available on the Van Doorne metal V-belt.

Two of the concepts introduce in this report are worthy of special note. First is the concept of converting efficiency data to torque loss data. Torque loss is defined as the extra torque required on the input shaft of the transmission in order to produce a specific output torque and speed. By setting up a table of torque losses, it becomes possible to make more accurate extrapolations of data to the low power areas and even to determine energy loss at zero output power.

The second important contribution is the concept of torque control. Most of the other investigators in this field envision ratio control, in which the control system instructs the transmission to assume a certain ratio of output speed to input speed. This ratio must be calculated by some means and appropriate changes made to the transmission control (for example, the swash plate angle in a hydraulic pump). The torque control concept is much simpler in many cases. The driver command is directly interpreted as an output torque command, with no intermediate calculation necessary. Furthermore, in the case of a hydraulic transmission, a specified output torque can readily be obtained by using a simple pressure control valve. Thus much of the complexity and many of the problems of stability which have plagued other control concepts can be eliminated.

Reference 7: Urban Transit Flywheel Propulsion Study
Author : Eberhart Reimers
Agency : U.S. Army Mobility Equipment and Development Command
Date : September 1976

Abstract:

The study results establish the feasibility of using high energy density flywheels with energy storage capacities up to 10 kilowatt-hours to operate future transit vehicles between automated electric charge stations located at enroute intervals of three miles or more. An analysis of suitable energy management systems for use with flywheels showed that a new type of electro-mechanical power-splitting transmission is best suited to the application. This transmission, consisting of a planetary differential with electric motor-generator bypass, provided smooth, highly efficient coupling of the flywheel to the vehicle wheels and is compatible with an electric charging interface.

Comments:

The study is oriented to concepts which use periodic wayside recharging. Heat engine/flywheel concepts were considered but rejected in order to completely eliminate dependence on petroleum. Numerous schemes for wayside recharging (hydraulic, mechanical, pneumatic, electric) were considered and it was concluded that electric power was the only practical solution. This in turn strongly biased the choice of transmission toward electric power.

The "electromechanical" transmission which they define is an electrical analogue of a hydromechanical split-torque transmission, i.e., some of the power is transmitted electrically and some mechanically. The concept is not sufficiently defined for an outside reader to conduct an evaluation, i.e., gear ratios are not defined, nor are motor or power conditioner characteristics. (This concept is also investigated in Ref. 6 for application to automobiles).

The report ends with a rather ambitious set of recommendations.

Reference 8: Study of Heat Engine/Flywheel Hybrid Propulsion Configuration with Electrical Transmission System

Report No. : ALO-41/1

Author : Anon.

Org. : Garrett-AiResearch

Date : April 1978

Abstract:

This nine month study was performed by Garrett-AiResearch for the Department of Energy (DOE) to conceive and evaluate a flywheel/electrical transmission. Three types of transmission were considered: DC-DC, AC-DC, and AC-AC. Each transmission option was evaluated and ranked according to cost, weight, and fuel economy over the LA-4 driving cycle. The vehicle used for the evaluation was a 1985 five-passenger family sedan with a parallel propulsion configuration.

It was determined that the AC-AC transmission system (option 3) is the most attractive for vehicular applications in the weight range investigated. A comparison was made between a conventionally propelled (heat engine/automatic transmission) vehicle and the same vehicle configured with the hybrid propulsion arrangement that utilized the selected AC-AC transmission system. The conventional vehicle has a curb weight of 3,000 lb., whereas the same vehicle configured with the hybrid arrangement has a curb weight of 2866 lb. Both vehicles have the same acceleration and pass maneuver performance. The capability for steady-state hill climb up a 5-percent grade, which established the heat engine size, is limited to 55 mph for the hybrid vehicle. This is in compliance with study requirements. The hybrid's fuel consumption is 39.5 mph, compared to 15 mpg projected for the conventional vehicle. This represents a 263-percent improvement and also exceeds any postulated Federal economy standards. The hybrid also provides a 40-percent savings in direct operating cost to the consumer. These benefits are derived for $2330 increase in vehicle retail (sticker) price.

Comments:

This report is concerned with passenger automobiles, but the results should have some applicability to buses.

Garrett Corporation is among the most aggressive at advancing the state of the art of power systems. Whereas other groups are content to rely on the proven DC traction motor, Garrett shows there are significant advantages to an AC drive, if only the problems of power controllers can be solved. They gave the informed reader considerable confidence that a technically sound solution to this problem is available. From a standpoint of economics, however, the solution remains questionable.

The major advantage of using an AC motor for traction is that the weight can be about 25 percent of that of a comparable DC motor. The advantage of using an AC motor coupled to the flywheel is that the flywheel and motor may be placed in a hermetically sealed enclosure, eliminating the need for rotating seals. Somewhat inexplicably, however, in this report Garrett recommends using similar AC motors for each purpose, perhaps in deference to the bilateral nature of the power flow. No explanation is given as how the heat generated in the vacuum chamber by the field coils is to be dissipated. This is all the more puzzling as an earlier Garrett report (Ref. 3), went into this important issue in some detail and recommended a homopolar inductor motor, which can have stationary field coils outside the vacuum chamber.

The AC to AC system is based on three recent technological advances:

1) Development of thyristors that can withstand high surge currents.

2) Development of reliable compact rotor-position sensors.

3) Microprocessors that can compute gates, time delays, counters, thresholds, etc., for switching the thyristors on and off.

In contrast to the sophistication shown in designing the power controls, the energy management logic chosen by Garrett is rather simple-minded. Essentially, the engine supplies the steady-state power, and the flywheel supplies transients. Very little discussion takes place as to how the system distinguishes between a change in the steady-state and a transient, and there is no comparison with the "on-off" control mode. More work in this area would be required to get a true assessment of their system.

Reference 9: Flywheel/Diesel Hybrid Power Drive: Urban Bus Vehicle Simulation

Report : UMTA-MA-06-0044-78-1

Author : G. S. Larson and H. Zuckerberg

Org. : Transportation Systems Center

Date : May 1978

Abstract:

A flywheel/diesel hybrid power drive configuration for urban transit bus application is investigated, using a computer simulation model. The hybrid uses continuously variable ratio transmissions and a control subsystem to optimize fuel consumption in an "on-off" mode of engine operation. The system is projected to use 50% less fuel than a diesel-alone in urban driving cycles having more than 4 stops per mile. Regenerative braking is used, contributing to fuel consumption improvement. The computer simulation model developed as a major tool for this investigation is described in detail.

Comments:

This report is mainly concerned with development of a computer simulation and does not go into any detail concerning CVT hardware. A brief review of previous work is included, much of which is copied verbatim from the Aerospace Report (Ref. 5). For the simulation a constant CVT efficiency of 77 percent is assumed. Two driveline concepts are investigated, a series scheme with two CVT's (Engine-CVT-Flywheel-CVT-Drive Wheels) and another series configuration with only one CVT (Engine-Flywheel-CVT-Drive Wheels). The latter scheme was used in conjunction with the "on-off" mode of operation and turned out to be the most practical.

Reference 10: Improvement of City Bus Fuel Economy Using a Hydraulic Hybrid Propulsion System

Report : SAE Paper No. 790305

Authors : P. Buchwald, G. Christensen, H. Larsen, and P. Sunn Pedersen

Org. : Technical University of Denmark

Abstract:

The paper describes the application of a hydraulic pump/motor and a hydro-pneumatic energy-storage as a supplement to the conventional internal combustion engine in a city bus.

The resultant hybrid-system makes it possible to smooth out the combustion engine power output and to regenerate the braking-energy which conventional buses dissipate as heat.

Computer-simulation and supplementary experiments with a model-system have shown that, depending on the driving pattern of the bus, this type of hybrid-system would lead to a 10-30% fuel saving provided that an appropriate control strategy is used.

Comments:

One of the interesting features of this paper is the schematic notion the authors develop for showing various hybrid transmission schemes. Generic diagrams are shown for conventional, series, parallel, and compound transmission power flow paths. This differs from the schematic diagrams of references 5 and 8 in being applicable to all transmission concepts: fluid, electromagnetic, and mechanical.

There is also a very useful graph of power density versus energy density for hydraulic accumulators, flywheels, superflywheels, and batteries. The authors chose hydraulic storage, even though the associated energy density is a factor of 30 less than that of batteries. This was based on component reliability, availability, and efficiency.

The question of control strategy is investigated in some detail. Three strategies were analyzed:

1) On-off control
2) "Best Efficiency" control
3) "Constant Engine Torque" control.

The simulations showed that the on-off strategy gave almost identical fuel economy to that of the other schemes. Thus, in agreement with References 6 and 9, they conclude that this is the preferred strategy, since it is the simplest.

Reference 11: Near-Term Electric Vehicle Program Phase II Mid-Term Summary Report

Report No. : SAN/1213-02 (DOE)

Org. : Garrett AiResearch

Date : August 1978

Abstract:

This document was prepared by AiResearch Manufacturing Company, a division of the Garrett Corporation, under Contract EY-76-C-03-1213 for the Department of Energy (DOE). It presents the mid-term review summary for Phase II of the Near-Term Electric Vehicle (NTEV) program.

The vehicle being developed is an all new design, highly optimized for the particular requirements of a small, four-passenger, electric-powered urban/suburban car. The power system is a new and unique design that uses flywheel energy to supplement battery power during peak demands and incorporates a regenerative braking feature to convert vehicle kinetic energy into retrievable flywheel energy during deceleration and braking. The process of energy storage and conversion to propulsive power is accomplished by a unique arrangement of the flywheel, two motor/generator units, and a power drive connected through a differential planetary gear set that functions as a fully automatic, infinitely variable transmission. The result is a highly efficient electric vehicle that requires a minimum of batteries while providing acceptable performance and driving characteristics that are similar to those of conventional internal combustion engine powered compact cars.

A description of the Eagle-Pitcher tabular lead-acid battery and its predicted performance are included, as is a discussion of the analytical modeling used for the performance evaluations. Sensitivity studies that have been used to evaluate some of the more critical aspects also are discussed.

A detailed description of the unique power system and its operation is given. The design of the laminar composite flywheel is described, and endurance test results are included. The high-vacuum system, which uses a molecular pump, is described and test verification of its design is given. The design of the two identical dc motor/generator units is described in detail. The electronic control system, which includes the two field controls and the battery current supply, is described and detail schematic diagrams are presented.

Comments:

Once again, General Electric and Garrett are competitors in a large systems contract, this time the Near Time Electric Vehicle Program for DOE. This document is actually made up of two reports, one from each contractor. The GE vehicle uses simple battery power with a DC traction motor and hence is of little interest from a standpoint of variable transmissions. The Garrett vehicle, on the other hand, uses a flywheel with a split-torque electro-mechanical transmission. The flywheel serves to level the load on the battery and to greatly enhance the regenerative braking capability of the vehicle. Recall that this particular transmission had been mentioned as a possibility in Refs.'s 4, 6, and 7. Its main advantage is that a substantial portion of the power flows from the flywheel to the wheels via a direct mechanical path, so that the overall efficiency is much greater than that of the combined motor/generator efficiencies.

With this contract report, Garrett completes the spectrum of electric transmission options. Their UMTA-sponsored effort, Ref. 3, had recommended a DC traction motor and an AC flywheel motor. A later report for DOE Ref. 8, recommended AC for both motors. Finally, in this report both motors are DC. No doubt Garrett had good reasons for choosing each particular option, but it does illustrate that the choice is never obvious. Extensive evaluation may be required before it can be determined which combination is truly the best for any given design requirement.

The desirability of using a flywheel for load leveling in a battery-powered vehicle is inadvertently illustrated in the portion of this document written by GE, whose design did not include this item. Their simulations showed a significant range penalty operating over the specified J227a driving cycle, so modifications were made to the cycle to allow constant battery current during acceleration, with consequent limitations on performance. Furthermore, much testing was devoted to determining the ability of a battery to accept a high charging rate during deceleration. The results of these tests showed that not only would the battery fail to capture the energy of a rapid charge, most of this energy went into the process of electrolysis rather than recharging. The result was sometimes violent outgassing of hydrogen.

Reference 12: Magnetic or Electro-magnetic--The Great Divide

Source : Electronics and Power, Vol. 19, No. 14, pp 310-312

Author : E. R. Laithwaite

Org. : Imperial College, London

Date : August 1973

Abstract:

Electric motors are classified as being magnetic or electromagnetic. In the former class are reluctance motors or hysteresis motors in which there is magnetomotive force on only one side of the airgap. The electromagnetic class includes the bulk of electrical machinery and is distinguished by having magnetomotive force on both sides of the airgap. A "goodness factor" is defined which serves as an indicator of the performance of electromagnetic machines, in terms of power factor and efficiency. It is shown that as electromagnetic machines are made large and larger, their goodness improves, whereas magnetic machines show improved characteristics at the smaller sizes.

Comments:

Professor Laithwaite's goodness factor has received considerable acceptance in the analysis of induction motors, particularly linear motors, although it may not be as useful for synchronous and DC motors. The paper was written with high speed ground transportation in mind, but it can be used to support the notion that electromagnetic transmissions may make sense for larger vehicles such as buses and trains, whereas they may not ever achieve widespread commercial acceptance in smaller vehicles such as automobiles.

Reference 13: An Analytical Study of Transmission Modifications as Related to Vehicle Performance and Economy

Report No. : SAE Paper No. 770418

Authors : H. E. Chana, W. L. Fedewa, and J. E. Mahoney

Org. : General Motors

Date : March 1977

Abstract:

A method of vehicle performance measurement has been developed so that selection of optimum fuel-economy performance trade-offs can be made for a vehicle having various powertrain components. This method was utilized in an analytical study of drivetrain component features such as--overall ratio range, number of ratio steps, locked converters, continuously variable drives, etc. Both manual and automatic type transmissions are considered. Indications are that ratio range is an important consideration in the selection of transmission design parameters and also conventional transmission concepts can be competitive with the more exotic continuously variable type units.

Comments:

This paper contains one perspective on CVT's which is missing from the other references; namely, that they should be compared to alternative future improvements to transmissions, rather than comparing tomorrow's CVT with today's transmission. The computer simulation which was used to predict fuel consumption of these various modifications was the result of more than ten years of development by GM, so it may be somewhat more realistic than some of the other simulations which have been reported.

Reference 14: Drive System with Brake-Energy Recovery

Authors : Faust Hagen and Paul Merker

Org. : MAN, Germany

Date : Circa 1979

Abstract:

Brake energy is an energy source which to date has been little exploited. City buses, which must brake frequently, lend themselves especially well to the use of this system.

Mechanical and hydraulic storage systems are suitable for storing recovered brake energy. M.A.N. has developed 2 test versions of each system, one being the gyrobus with mechanical flywheel storage and the other being the hydrobus with hydraulic storage.

It is the aim to develop drives which yield a reduction in fuel consumption of 15 to 20% as compared to conventional drives as well as improved drive characteristics, and lower pollution values while weight, installation space and procurement costs are to remain the same.

Comments:

The program developments reported in this document provide the most convincing evidence yet that a practical energy storage system can be developed for buses. This is one of the few reports which provides a comparison of the cost of the various energy storage systems versus the projected energy savings. The authors conclude that their "hydrobus" (hydraulic storage) can attain greater fuel savings because of the absence of stored energy loss during idling. On the other hand, the gyrobus is almost as fuel-efficient while being lighter and cheaper. The projected cost of a gyrobus is only 5 percent greater than that of a standard bus. A major reason for this small cost increase is the fact that the engine can be made smaller.

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