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AUTHOR(S): Milton C. Krupka and S. V. Jackson

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IMPACT OF FLYWHEEL ENERGY STORAGE TECHNOLOGY UPON TAXICAB FLEET OPERATION IN A LARGE METROPOLITAN CITY*

Milton C. Krupka and S. V. Jackson
Technology Assessment Group
Analysis and Assessment Division
Los Alamos National Laboratory
University of California
Los Alamos, New Mexico 87545, USA

ABSTRACT

The incorporation of flywheel energy storage systems (FESS) into automotive vehicles has been under consideration for some time. Previous studies have suggested that FESS can yield substantial benefits in automotive vehicle operation, particularly for urban driving.

This paper describes an assessment of the impacts resulting from incorporation of FESS into automotive fleets in a large metropolitan city. Specifically, the case of taxicab fleet operation within New York City is examined. Unique features of taxicab fleets are noted and taxicab operational characteristics within New York City are detailed. Based upon available New York City operational data, a levelized life-cycle cost comparison between a standard internal combustion engine vehicle (ICEV) in present use as a taxicab and a projected FESS/ICEV taxicab is generated. Energy-savings and environmental benefits are discussed, and potential institutional barriers to FESS implementation are identified.

The results obtained from this study generally emphasize the value of incorporating flywheel energy storage systems into future vehicles designed for taxicab use.

1. INTRODUCTION

The most important challenge facing the future development of the automotive vehicle is the issue of energy conservation. Stringent fuel economy and emissions control goals have been mandated for the forthcoming decade. Achievement of these goals will require new research and development initiatives, design and production engineering, and the successful demonstration of energy-saving technologies that can be introduced into automotive vehicles.

Automotive vehicles are the single largest users of petroleum in the nation. There are a number of ways usage may be reduced. One of the most promising is through the use of energy storage systems coupled with optimized designs of the engine and power train.

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The use of a flywheel energy storage system (FESS) in transportation applications has been advocated for some time [1]. Only recently, however, has interest in flywheel technology increased. This is due primarily to both the overall energy situation and the major advancements in materials science and engineering as applied to flywheel system development. Major developmental programs relating to flywheel applications within the transportation sector were conducted during the past decade by the Department of Transportation, Department of Energy (Lawrence Livermore National Laboratory) and several private organizations.

Studies and practical demonstrations have shown that the FESS can yield substantial benefits to automotive vehicle operation provided: (a) care is taken to minimize parasitic losses in the various components of the FESS-transmission system; (b) operation and driving patterns of the vehicle are accomplished in select modes, e.g., urban driving; and (c) engine designs are optimized.

The flywheel stores rotational kinetic energy. Rapid charge/discharge rates at high power levels are characteristic. Thus, the system provides a load-leveling function for the prime energy mover and the mover design can be optimized. In addition, the flywheel can recover the kinetic energy that otherwise would be rejected during deceleration (regenerative braking). Thus, additional energy will be available for later use, which again relieves the load on the prime energy mover.

The objective of the study is to present a preliminary assessment and evaluation of the economic, environmental, and energy-savings benefits of the introduction of a flywheel energy storage system into a standard internal combustion engine vehicle (ICEV). In particular, because benefits are presumably maximized for urban driving, the taxicab fleet operating in New York City is examined.

The study generates levelized life-cycle costs on the basis of available operating costs of the present-day taxicab ICEV and projected costs of a taxicab flywheel-hybrid (FESS/ICEV). Sensitivity studies for select parameters important for economic viability are made. In addition, potential improvements in emissions and energy savings are determined and several institutional barriers to implementation are identified.

2. AUTOMOTIVE FLEET VEHICLE MARKET AND TAXICAB SECTOR

Taxicabs operate primarily in two modes, either (1) as independent owner/drivers or (2) as fleets of vehicles ranging from a minimum of two or three (mini fleets) to several hundred. The fleet market, in general, is particularly valuable as a technological test market for new vehicle and component design such as flywheel systems because [2]:

a. availability of professional management and fiscal resources permits a higher degree of risk involvement;

b. maintenance, vehicle control, and record-keeping practices exist;

c. vehicles can be assigned to specific and well-defined missions;

d. mileage and operational data accumulate rapidly; and

e. there is high product visibility.

Because of the diversity of purpose existing within the fleet market, it is convenient to subdivide the fleet into a number of sectors, one of which is the taxicab sector. The taxicab fleet represents a small but significant entity in terms of its contribution to the transportation industry. Although the main service of taxicabs has been transportation of passengers, the industry is diversifying and including a variety of services categorized as "paratransit" activities. In this paper, only passenger transportation is considered.

The diversity of fleet vehicle usage results in a variety of criteria that fleet operators must contend with in selection of vehicles. In considering the purchase of vehicles within the taxicab sector, surveys have indicated that maintenance represents the primary purchase criterion with life-cycle costs and reliability close secondary criteria. This is perhaps better understood when it is realized that the operational environment for taxicabs is relatively severe especially those that operate more or less continually in congested central business districts (CBD).

3. NEW YORK CITY TAXICAB OPERATION

Both public regulatory and private sector agencies have provided data helpful for the characterization of New York City taxicab operation. Information was provided from several sources but major contributions were obtained from the New York City Taxi and Limousine Commission* and the Metropolitan Taxicab Board of Trade, Inc.,** an association of fleet taxicab companies.

Characterization of taxicab operation in New York City is difficult because there are several systems. There are approximately 12,000 licensed taxicabs, controlled by the New York City Taxi and Limousine Commission. About 50% operate as fleets and minifleets and the remainder as independent owner/drivers. There is also a substantial but indeterminate number of livery service vehicles (gypsies) operating within and without the city limits and not controlled by the Commission.

Characteristics unique to the New York City taxicab sector include: very high annual mileage accumulation (50,000 to 80,000 miles); relatively short vehicle lifetime (18 to 36 months); urban stop-go driving and significant braking; low average speed (about 7 to 11 mph) and low average gasoline mileage (about 10 mpg) in central business districts (CBD). Additional characteristics, operating parameters, and data used for the economic analysis are given in [3].

4. ECONOMIC ANALYSIS

A levelized life-cycle cost (LLC) methodology was used to perform the economic analysis. The advantage of LLC is that the total operating cost,

*New York City Taxi and Limousine Commission, 6[illegible] Wall Street, New York City, New York 10005.

**Metropolitan Taxicab Board of Trade, Inc., 24-16 Bridge Plaza South, Long Island City, New York 11101. This organization controls the fleet operation of about 2200 taxicabs, about 20% of those licensed.

including the capital investment, is characterized by a single number. A detailed discussion of LLC methodology is contained in the user's manual for the computer code (BICYCLE) used in this analysis [4]. The data used in the analysis reflect primarily that relating to fleet operation with estimates made where necessary. Three separate systems of interest were established for c[illegible]tional purposes. Results are shown in Fig. 1.

a. For fleet operation, the life-cycle cost for a FESS/ICEV is less by 3.3¢/paid mile. Although this may be a small percentage decrease relative to total costs, it should be noted that the bulk of the costs making up the total (e.g., driver/dispatcher) has little to do with FESS. Also, since the system is new, operating and maintenance (O & M) costs have been increased to reflect a conservative viewpoint at least for the early commercialization stage. These costs should decrease in time with due reflection in the life-cycle cost advantage.

b. The FESS/ICEV fuel cost (fleet operation) for the same annual mileage is less. This is implicit in the analysis.

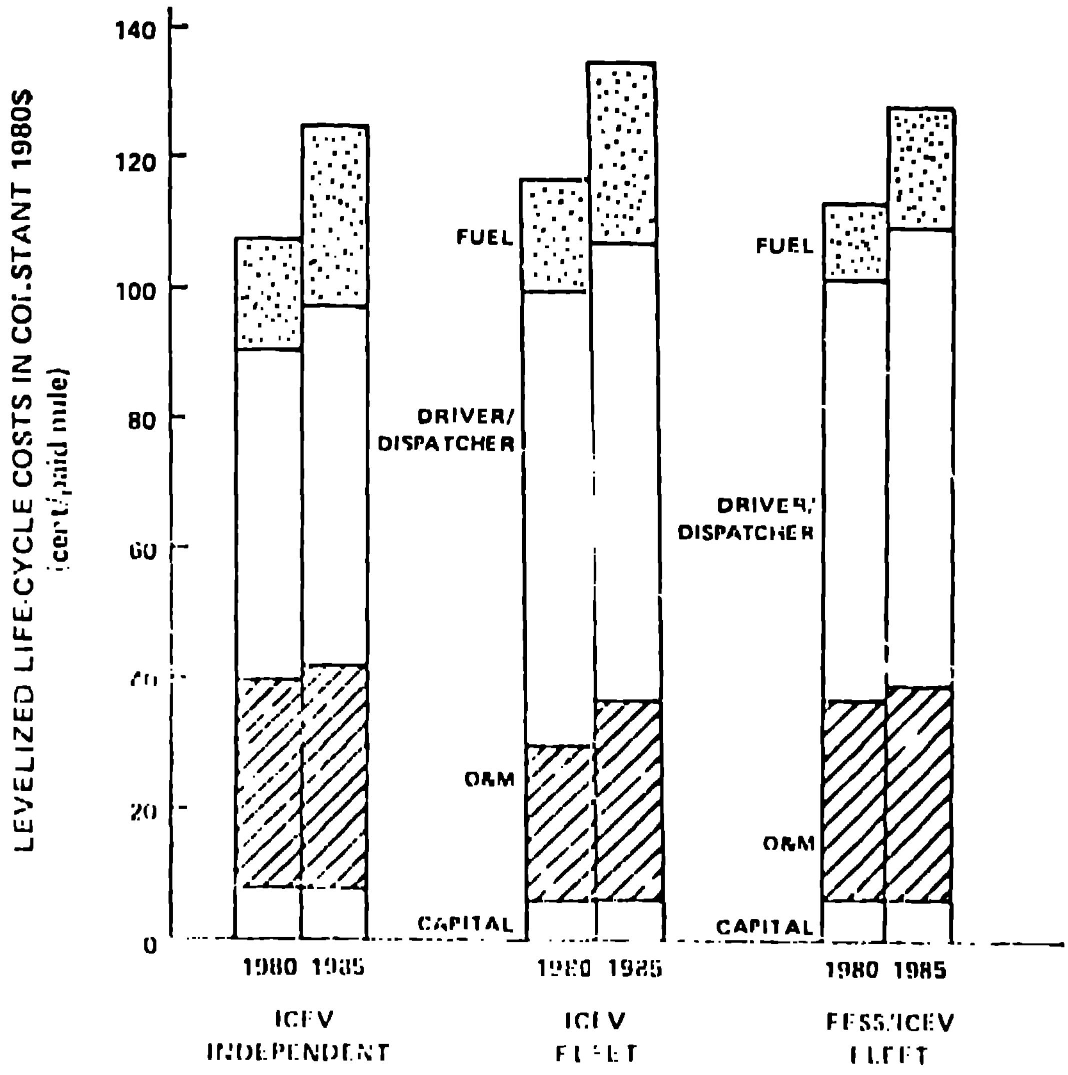

Fig. 1. Comparison of levelized life-cycle costs for three systems of taxicab operation.

c. The cost of driving and dispatch constitutes the major cost to all systems, 47 to 57%, depending on the system.

d. The capital costs are a small fraction of the total and are less than the costs of fuel. This suggests that further investments in capital may be warranted to insure additional fuel economy. In other words, should the FESS system be more costly than anticipated, investment may still be worthwhile.

e. Costs are indicated in paid miles, a factor of interest to both industry and regulatory agencies.

f. Total costs for the independent owner/driver vs. fleet ICEV are less primarily because of assumed driver labor and other financial parameter variation.

Data for 1985 are shown because this date is considered to be the earliest possible for introducing any significant quantity of FESS/ICEV taxicabs.

Sensitivity studies were performed on several parameters of interest. These include levelized life-cycle costs vs: (a) utilization factor; (b) FESS/ICEV fuel economy ratio; (c) FESS/ICEV-ICEV capital cost ratio; and (d) fuel cost. Results are shown in Figs. 2 to 5. Only fleet operation data were used in these studies.

Life-cycle costs are somewhat less for a FESS/ICEV system at all utilization factors (Fig. 2). At 100% utilization, paid and total

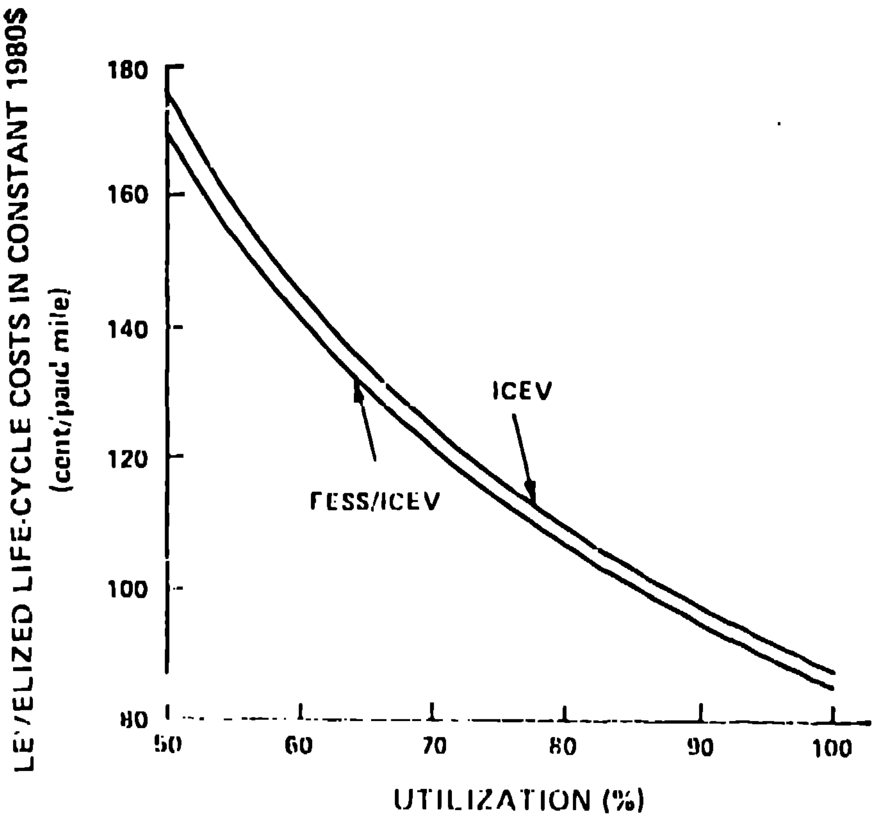

Fig. 2. Life-cycle costs (fleet operation) of taxicab ICEV and FESS/ICEV as a function of the utilization factor.

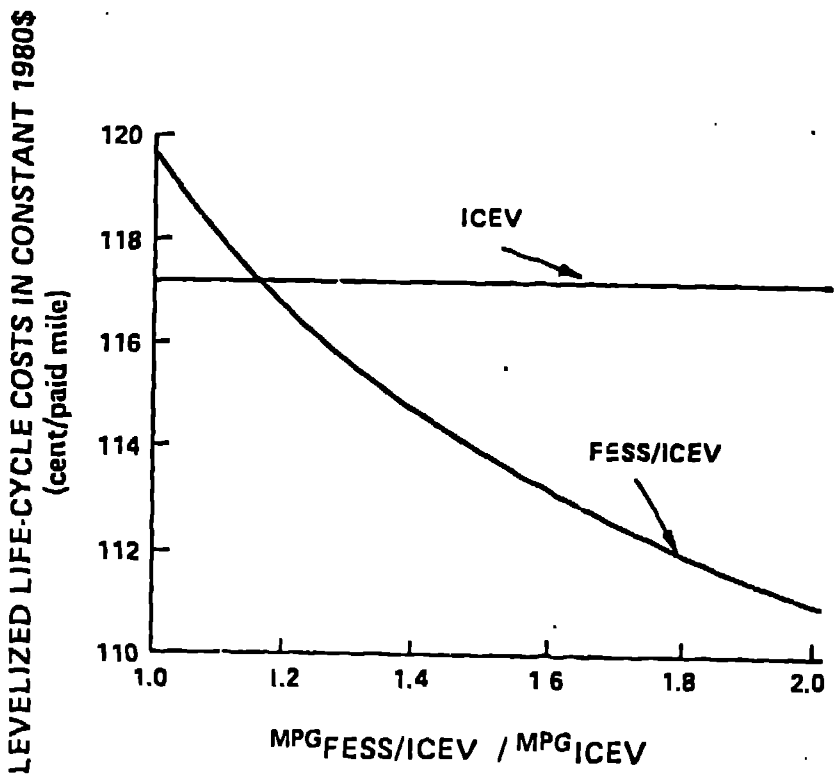

Fig. 3. Life-cycle costs (fleet operation) of taxicab ICEV and FESS/ICEV as a function of fuel economy ratio.

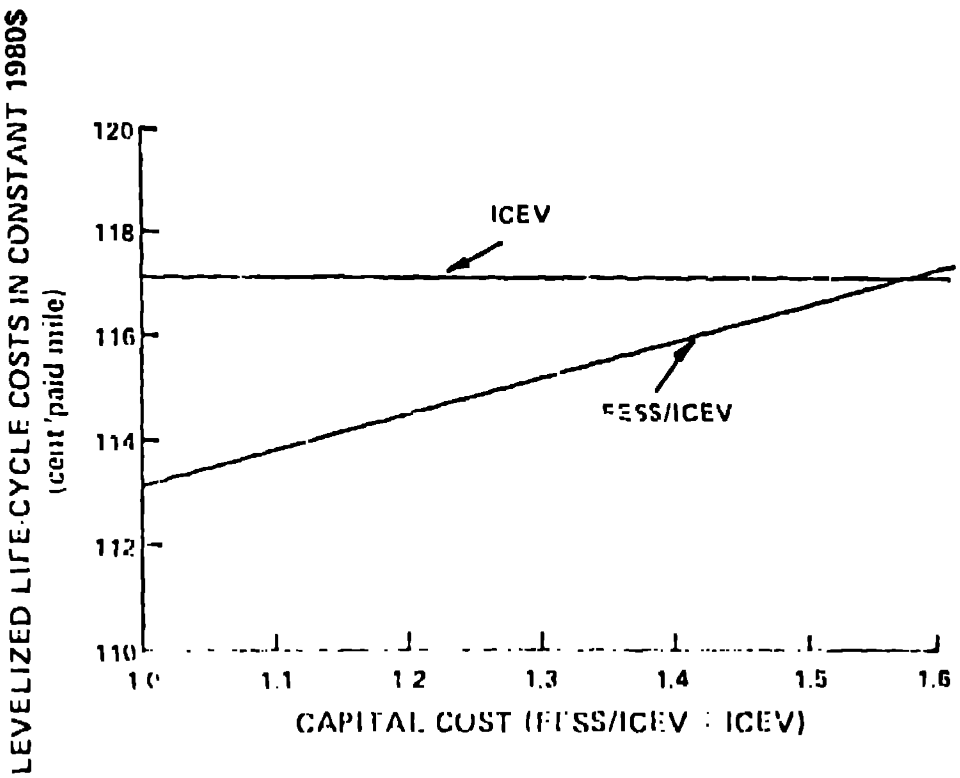

Fig. 4. Life-cycle costs (fleet operation) of taxicab ICEV and FESS/ICEV as a function of capital cost ratio.

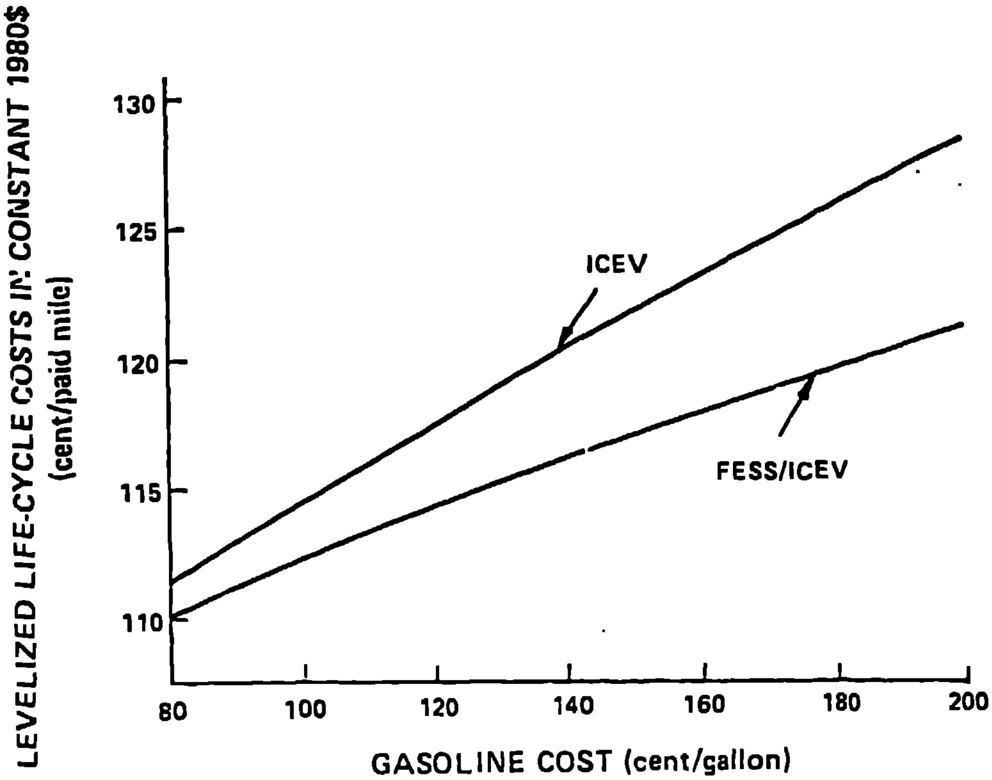

Fig. 5. Life-cycle costs (fleet operation) of taxicab ICEV and FESS/ICEV as a function of gasoline cost.

transportation miles are coincident. In 1975 utilization averaged about 53 to 56%. The higher utilization (about 75%) for New York City is in part due to a heavier concentration of licensed fleet vehicles in the CBD whereas the 1975 data represents national averages in many areas. As might be expected, benefits increase with higher utilization rates.

Life-cycle costs of FESS/ICEV are reduced with continued improvement in fuel economy relative to a base value 10 mpg (1.0 ratio) for the ICEV (Fig. 3). The breakeven gasoline mileage is about 11.8 mpg. Operating costs are higher for FESS/ICEV above the breakeven point.

The life-cycle cost vs. the capital cost ratio is of particular interest (Fig. 4). It suggests that the capital costs for a FESS/ICEV could be increased as much as 50% before exceeding the ICEV life-cycle costs. This additional capital investment would be warranted to achieve projected gains in fuel economy.

The FESS/ICEV system is less costly at all values of gasoline cost shown in Fig. 5. An interpolation would demonstrate breakeven cost at about 60 to 65¢/gal in this study. As fuel costs increase, the FESS/ICEV becomes progressively more economical.

5. ENERGY CONSERVATION ANALYSIS

Fuel consumption for a given vehicle in specific driving modes is determined by the complex interaction of: (a) several engineering features of the vehicle; (b) traffic control systems; and (c) individual driver reactions to the specific situation that arises.

The gain in fuel economy projected to come from FESS in a vehicular application is the result of not only the regenerative braking concept but also the concurrent efficient operation of an optimized engine and drive train system. This combined engineered system has been studied by several groups, notably the University of Wisconsin, for a number of years. A 3000 lb (1364 kg) vehicle was built and tested over the Federal Urban Drive Cycle and demonstrated a mileage improvement of about 50 percent over a corresponding standard production vehicle [5]. Further, simulation studies have shown that a 75% improvement is feasible with currently available system components and that, with continued research and development, a possible 100% may be reached. Applied to the taxicab industry generally and to the operations in New York City, these results are significant.

Savings in fuel by New York City licensed taxicabs can be shown directly, assuming the 50% gain in fuel economy, i.e., from 10 mpg to 15 mpg for fleets and from 12 mpg to 18 mpg for the independents [3]. This increase in mileage per gallon translates to a 33.3% savings in fuel purchases annually for the same total annual mileage. There are about 12,000 licensed taxicabs in the city, which accumulate 80,000 and 50,000 miles per year (fleets and independents, respectively). A prorated calculation shows the total amount of gasoline saved to be 25×10^6 gal/year. The energy equivalent of automotive gasoline is about 125,000 Btu/gal. Thus, about 3.1×10^{12} Btu/year can be saved. At a cost of \$1.20 per gallon of gasoline, the savings for the entire fleet is \$$30 \times 10^6$/year. Practically speaking, these savings will be reduced by some fraction because of inclusion of some percentage of extended urban and highway travel.

Although it it tempting to extrapolate these numbers to the national taxicab fleet (about 207,000 vehicles) [6], it should be understood that taxicab operation in New York City is by no means equivalent to those in other cities. There are too many other variables such as urban design, traffic control, system variation, and inclusion of available freeway traffic. For example, it has been shown that about 45 percent more gasoline is used in the New York City/Newark CBD compared to the Los Angeles CBD to travel the same distances [7]. The fraction of the national fleet that drives in a manner equivalent to that in New York City is unknown.

[illegible]. ENVIRONMENTAL CONSIDERATIONS

The introduction of flywheel technology is likely to have its most noticeable effects upon air quality (emissions) and associated health impacts, especially in urban environments. Because CBDs have the highest pollution levels, the emissions study focused on Manhattan, New York City's prime CBD.

The New York City Taxicab and Limousine Commission mandates strict emission standards. Licensed taxicabs must undergo emission checks three times yearly on both spot check and scheduled bases (noncontrolled livery service cabs - once yearly). This check includes engine idle exhaust analyses (about two minutes).

The introduction of FESS into taxicabs by 1985 and beyond should reduce emissions further due to fuel usage reduction (beyond evolutionary engine and [illegible] design improvement).

The use of FESS, through its regenerative braking function, also reduces [illegible] from the brake system because brake lining wear should [illegible].

Flywheel rotors operate within a vacuum (< 1 torr) so as to reduce, among other effects, aerodynamic heating. Should the pressure rise to ambient while the rotor is spinning rapidly, the potential exists for a gas molecule-surface interaction that will cause overheating and in the case where composite rotors are used, a possible fire. Combustion of organic materials releases gases and particulates. The exact nature of these combustion products or emissions will depend, in part, upon the specific parent materials. Proper design engineering should minimize such occurrences.

Because New York City also regulates noise levels, any noise problems presently encountered in development should be solved before introduction into the city environment.

7. INSTITUTIONAL ISSUES

A number of institutional barriers that may visibly affect deployment of FESS/ICEV vehicles in the taxicab market sector have been identified. These include:

a. the automobile industry production infrastructure as it relates to the market for taxicabs. The number of vehicles classified as taxicabs is small. The passenger vehicle industry has huge capital investments, and the research and development activities tend to emphasize evolutionary modifications. The economies of large scale production may inhibit immediate FESS production unless the total market is enlarged, i.e., to levels more consistent with national passenger vehicle numbers. If not, the resulting "specialty" market may produce items with higher price tags and, for the short term, there could be limited availability of components.

b. lack of maintenance and service information for the taxicab industry, which prefers relatively short downtime periods. Considering the general design of FESS and associated controls, additional service requirements may be anticipated including new training and reorientation for mechanics.

c. the ownership of patent or commercial rights relating to component development by contractors using government funds. This problem pervades many other programs sponsored by Federal agencies. Generally, the contractor is not permitted to retain these rights. Thus, the success of an individual company, especially a small one, may be at stake. The net result is often a delay in market penetration despite the availability of technology and operating fleet vehicles.

d. the necessary education of regulators, liability insurers, and the public with respect to the safety of FESS. Safety considerations have not been previously discussed in terms of the technical aspects. Nevertheless, the safety issue cannot be ignored in an institutional sense. Insurance companies will want information such as safety test data, crash effects, and damage repairability before issuing liability policies. This is especially important in the New York City area. A question that will be asked is whether or not the flywheel introduces a degree of hazard beyond that of the present type of ICEV. Product liability with respect to the manufacturer also concerns the insurance industry. Some minimal and additional Federal safety standards may have to be developed for FESS/ICEV especially if new hazards are shown to exist. At the moment, there is no proven track record for the system, although fail-safe designs may exist. A strong educational program for the insurers, the public and the state, and municipal vehicle registration and regulatory agencies will be required.

Certain other institutional barriers are described in [3].

On the more positive side, a precedent is available in New York City regarding taxicab fleet advanced technology demonstrations. Recently, successful tests of diesel engine-powered taxicabs have been completed [8]. Generally, various other regulations in New York City do not appear to be restrictive.

9. SUMMARY AND CONCLUSIONS

- The automotive fleet market provides a valuable test bed for advanced technology applied to the transportation sector.

- For the taxicab sector, the primary purchase criterion appears to be maintenance and parts availability with life-cycle costs and reliability running a close second.

- Characteristics unique to the New York City taxicab industry include: very high annual mileage accumulation (50,000 to 80,000 miles); relatively short vehicle lifetime (18 to 36 months); urban stop go driving and significant braking; low average speed (about 7 to 11 mph) and low average gasoline mileage (about 10 mph) in central business districts (CBD).

- Characterization of taxicab operation in New York City is difficult because there are several systems. Data obtained and used for the economic analysis reflect primarily that relating to fleet operation.

- A levelized life-cycle cost (LLC) methodology was used to perform the economic analysis. Results obtained suggest that:

  a. flywheel-internal combustion engine vehicle (FESS/ICEV) costs are less/paid mile than those of the ICEV;
  b. the capital costs represent a small fraction of the total and are less than fuel costs in both categories;
  c. the cost of driving and dispatch is the major cost in both categories.

  Sensitivity studies performed on several parameters emphasize the value of FESS in taxicab operation in New York City.

- An analysis of energy-savings based upon a conservative 50% increase in fuel economy (due to FESS incorporation into an ICEV) suggests a significant savings in fuel purchases for equivalent annual accumulated mileage.

  Environmental improvement in the form of reduced emissions is to be expected with the introduction of FESS/ICEV taxicabs.

  A large-scale demonstration test would provide a more accurate evaluation of the benefits suggested by this study.

REFERENCES

1. [illegible]. J. Lawson, "Is There a Flywheel in your Future?," Engineering Know-How in Engine Design - Part 21, SAE SP-379 (March 1973).

2. J. R. Wagner, "Fleet Operator Data Book (Summer 1977 Data); National Data," 1, BNL-50904 (September 1979); Regional Data, 2, Draft (July 1980).

3. M. C. Krupka and S. V. Jackson, "A Preliminary Assessment of the Impact of Flywheel Energy Storage Technology on Taxicab Fleet Operation in a Large Metropolitan City," LA-8722-MS (February 1981).

4. R. W. Hardie, "BICYCLE - A Computer Code for Calculating Levelized Life-Cycle Costs," LA-8493-MS (August 1980).

5. N. H. Beachley and A. A. Frank, "Flywheel Energy Management Systems for Improving the Fuel Economy of Motor Vehicles," Final report, DOT/RSPA/DPB-50/79/1 (August 1979).

6. Automotive Fleet, Bobit Publishing Company, Redondo Beach, CA (April 1980). Note--this is a monthly magazine.

7. M. F. Chang and R. Herman, "An Attempt to Characterize Traffic in Metropolitan Areas," Transporation Science, 12 (1) (February 1978).

8. K. M, Hergenrother, "Comparison of Fuel Economy and Emissions for Diesel and Gasoline-Powered Taxicabs," Final report, US Department of Transportation, UMTA-MA-66-0066-79-1 (July 1979).