History of Electric Vehicles in General Motors

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Abstract—**This paper traces the efforts by General Motors in the area of electric and hybrid propulsion systems. Propulsion systems developed for different vehicles are described and performance achieved is presented. The present activities to commercialize the electric vehicles are briefly examined. The paper concludes with recommendations of technologies to be applied in propulsion systems to bring the performance of the electric vehicles to the state that is viable for mass acceptance.**

Introduction

GENERAL Motors in its continuous search for better vehicle propulsion systems and to reduce vehicle emissions, has conducted extensive research and development in the area of electric and hybrid vehicles. GM's work with electric vehicles began in 1916 when GMC Truck produced a number of electric trucks using lead-acid batteries. With the development of electric self starter for the gasoline powered vehicles, interest in the development of electric vehicles disappeared. In 1953, GM built the Firebird I—the first gas turbine powered experimental automobile in the United States. In 1960's, due to the increasing awareness of air quality, GM again resurrected its research on electric and hybrid vehicle propulsion systems.

During the Arab oil embargo, electric vehicle development activity was pushed to the forefront. Gasoline prices fell during late 1970's, and thus the interest in the EV activity declined. In 1980's, environmental concerns once again became the prime motivation behind the EV effort. The GM IMPACT was developed in early 1990's out of concern for air quality. The IMPACT design is based on advanced propulsion system technology and was designed suitable for mass production at an affordable cost.

This paper reviews several of the electric and hybrid vehicles developed by GM over the last three decades. Specifically, the propulsion systems utilized in these vehicles are described and the performance of each vehicle is presented. The specifications and performance achieved by various vehicles are summarized in Table I.

I. Electrovair [1]–[4], [8], [13]

In 1964, GM's Engineering Staff produced the Electrovair I, built on a 1964 Chevy Corvair body and chassis. In 1966, Electrovair II was built on a 1966 Corvair body and chassis as shown in Fig. 1.

Motor	Three phase Induction Motor (oil cooled), 115 HP, and max. speed of 13,000 rpm.
Battery	Silver-Zinc battery pack, 512 V, and 680 pounds
Inverter	dc to ac inverter based on SCRs
Top Speed	80 mph
Range	40 to 80 miles
Acceleration	0–60 mph in 15.6 s.
Vehicle Weight	3400 lb.

Although it was recognized that silver-zinc batteries were too expensive to be ever practical for passenger automobile, they were elected to power the experimental cars since they represented the most advanced type of battery system at that time for vehicle propulsion. The batteries had extremely short cycle life and long recharge time, heavy weight, short range, costly components and materials, and difficult cooling requirements. Despite all the problems, the high-performance electric drive system enabled it to achieve accelerating performance comparable to that of the standard 1966 Corvair. The technology of the 1960's was not mature enough to produce a commercially viable electric vehicle.

II. Electrovan [1]–[5], [8], [13]

In 1966, GM joined with Union Carbide Corporation and demonstrated electric propulsion with fuel cells in a van. This was called Electrovan shown in Fig. 2. The 1966 GMC Handivan was converted to build the Electrovan. This was the first fuel cell van ever to be built.

Motor	3 phase induction motor, 125 HP
Battery	Based on hydrogen–oxygen fuel cell system. The fuel cell comprised 32 modules with continuous power capability of 32 KW and 160 KW for short duration required for acceleration.
Inverter	dc to ac inverter using SCRs.
Top speed	70 mph
Range	100 to 150 miles
Acceleration	0–60 mph in 30 s.
Vehicle Weight	7100 lb

The electrovan was devoted primarily to study the problems of powering a passenger vehicle with a fuel cell and its interaction with electric drive system. Problems in-

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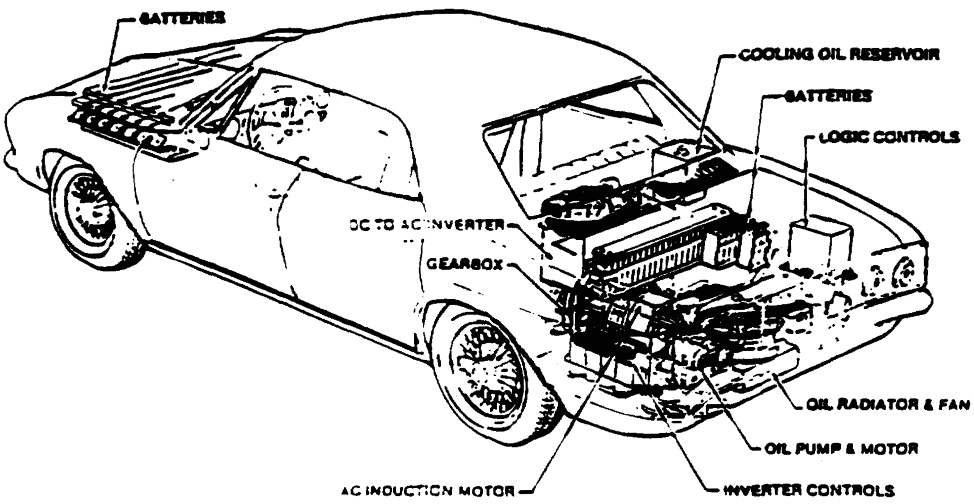

Fig. 1. Cutaway view of General Motors Electrovair.

TABLE I
GM Electric Vehicles Specifications and Performance

PROJECT	Electrovair	Electrovan	Military 6x6	Stir-lec I	GM512 Electric/ Hybrid	AT&T Van	Electrovette	Impact	Impact 3	Indy Electric Shuttle
CONVERSION OF:	Chevrolet Corvair	GMC Handivan		Opel Kadett '68		GMC	Chevrolet Chevette			
CATEGORY	Cars	Vans	Trucks	Cars	Cars	Vans	Cars	Cars	Cars	Buses
ORIGINATION YEAR	1966	1968	1968	1968	1969	1979	1979	1990	1993	1993
TOP SPEED (mph)	80.00	70	50	55.00	40	50	60	110.00	75	52
CURB WEIGHT (lbs)	3400	7100		2930				2200	2910	11000
No OF MOTORS	1	1	6	1	1	1	1	2	1	2
BATTERY TYPE	Silver-zinc	Fuel Cell (32 modules)		Lead-acid	Lead-acid	Lead-acid	Nickel-zinc	Lead-acid	Lead-acid	Lead-acid
No OF BATTERIES				14	6	18		32	26	2 x 26
BATTERY VOLTAGE				12	12.0	12		10.0	12.0	12
PACK VOLTAGE	512.0			168	72.0	216	120	320.0	312	312.0
ENERGY (A-h)				44.0	85.0	76	150	42.5	54	104.0
MOTOR TYPE	Induction	Induction	Synchronous (Brush-less)	Induction	DC - Field (Brush)	DC - Field (Brush)	DC - Field (Brush)	Induction	Induction	Induction
CONT. POWER (hp)			20		8.5		23	20		
PEAK POWER (hp)	115	125		20		50	33	57	137	94
SPEED (rpm)	13000		22000	12,500				12,000	12,000	9000
INVERTER TYPE	SCR	SCR	SCR	SCR	SCR	SCR	SCR	MOSFET	IGBT	IGBT
HYBRID ENGINE			GMC 302ci (6 cyl.)	Stirling GPU (1 cyl.)	11.7ci (2 cyl.)					
ENGINE POWER (hp)			140	8						
CONFIGURATION			Series	Series	Dual Mode					Series
GENERATOR TYPE			Brushless homopolar induc.tor	Alternator (3 phase)	20A 90V alternator					PM Synchronous
GENERATOR PWR (KW)			100	19 KVA	1.8 KVA					18
ACCELERATION (secs)	15.6	30		10		12	8.3	8	8.5	8
FROM (mph)	0	0		0		0	0	0	0	0
TO (mph)	60	60		30		30	30	60	60	30
RANGE (miles)	60	125			5.2 (Elect.)	40	60 EPA	120	70 EPA	40 (Elect.)
AT SPEED (mph)					30			55	90 Hwy	35

cluded heavy weight and large volume, costly components and materials, complicated and lengthy start-up, and shut-down procedures, gas leaks, electrolyte leaks, complexity of three separate fluid systems (electrolyte, hydrogen, and oxygen). The power converter was complex, especially the provisions of the capacitors and commutating circuits required to supply the reactive KVA of the motor. The entire system was too expensive and complicated.

III. Electric Truck For Military Application [6], [7], [12]

In 1968, the Delco Remy Division of General Motors developed an electrically powered six-wheel military vehi-

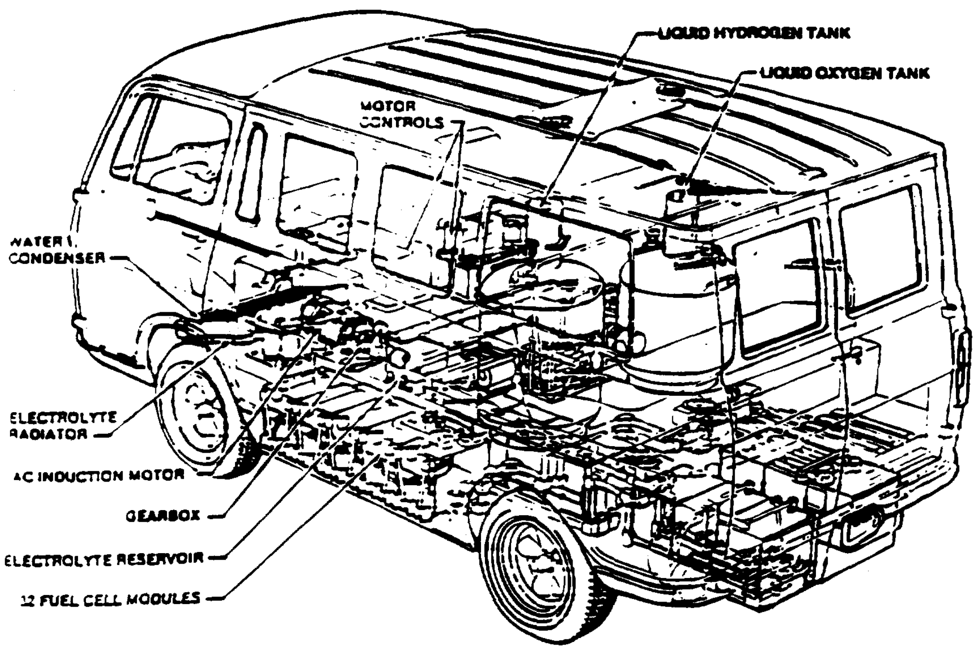

Fig. 2. Cutaway view of General Motors Electrovan.

cle capable of transporting freight up a 60% gradient. The system employed a GMC 302 cubic inch, six cylinder, gasoline engine to drive an ac generator, which converts the mechanical energy to electrical energy sufficient to propel the vehicle up to speeds of 50 mph with a seven-ton cargo. Alternator output was fed to the SCR based power converter packages. The output of each power converter was fed to a wheel motor. All the six wheel motors and the power converters were liquid cooled. The engine alternator loop coordinates the engine throttle and alternator field control as a function of the operator's command through the accelerator pedal. The output of the alternator field control provides excitation to the propulsion alternator field.

Engine—6 cylinder gasoline, 168 gross, 140 net HP at 3500 rpm, 243 lb/ft maximum at 1400 rpm.

Propulsion alternator—Brushless homopolar inductor alternator; 100 KW nominal; liquid cooled; frequency 3500 Hz at 15,000 rpm; SC Current 900 amp; excitation 28 V, 840 W, externally excited; speed 15,000 rpm nominal.

Propulsion motor

Type	Brushless synchronous motor with dc motor characteristics
Speed	Infinitely variable from 0–17,000 rpm, over speed to 22,000 rpm
Cooling	Liquid, rotor not cooled
Rating	Nominal 20 HP over 16:1 speed range, continuous 1000–16,000 rpm
Frequency	850 Hz at 17,000 rpm
Gear ratio	33.8:1 reduction, two stage planetary system.

Power converter

Type	18 SCR square wave cyclo-converter
Cooling	Liquid
Weight	23 lb ready to install
Thyristors	800 V, 110 ampere rms rating

The vehicle was extensively tested in GM proving grounds. The attributes were:

- Effective dynamic braking in a simple and reliable configuration.
- Significantly improved fuel consumption when compared to a conventional truck.
- Wide torque-speed range with no gear changes or electrical switching resulting in an infinitely variable transmission.
- Automatic wheel speed control in which there was no wheel runaway with loss of traction.
- Engine operation flexibility for fuel economy, emission control, acceleration, or a combination of these.
- System stability for all conditions of operation.

Many advantages for an electric drive system were demonstrated and verified. The resulting incentives for application to military vehicle being: improved reliability, vehicle design freedom, engine operation flexibility, adaptability to variety of engines, and new vehicle concepts.

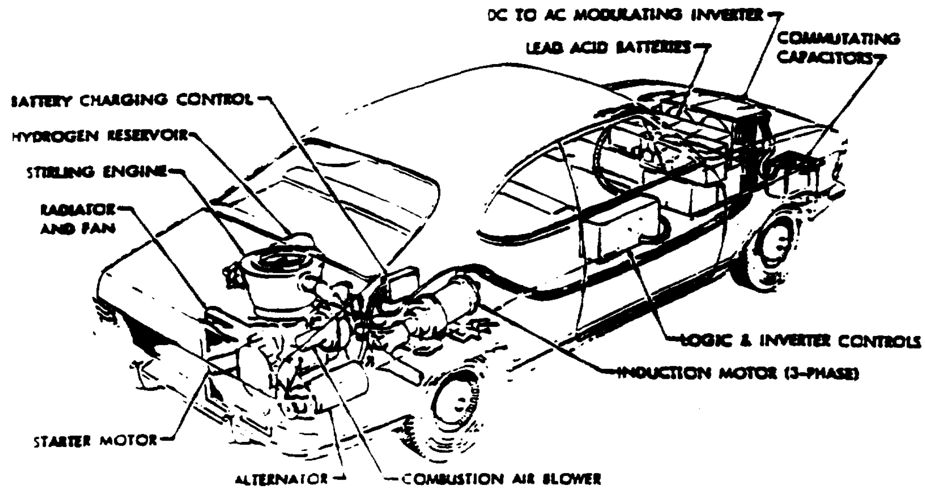

Fig. 3. Cutaway view of Stir-Lec I.

The tests demonstrated the incentives of using hybrid propulsion system. No major failures were encountered.

IV. Stir-Lec I, A Stirling Electric Hybrid Car [4]

In 1968, GM Research Laboratory engineers built an experimental electric hybrid vehicle using a small Stirling engine, to explore the use of a low emission and electric drive system in a small car. The Stirling engine is an external combustion engine where the fuel is burned in a separate burner and it can use any of a wide variety liquid fuels, such as unleaded gasoline, diesel fuel, or kerosene. The exhaust from this engine has low amounts of carbon monoxide and smog forming hydrocarbons.

The vehicle chosen for this study was 1968 Opel Kadett, because of its smaller size. The Stirling engine was not mechanically coupled to the driveline but drives a three phase alternator, the output of which is rectified to charge the batteries. A cutaway view of the Stir-LEC I car is shown in Fig. 3. The population system consisted of:

Stirling engine—Model GPU-3, single cylinder; 8 HP at 3000 rpm; working gas—Hydrogen Pressure—1000 psi

Generator—3 phase alternator, 19 KVA nominal rating, Design speed of 5500 rpm.

Motor—Three phase induction motor 20 HP; Motor speed at 55 mph is 12,500 rpm.

Inverter—Three phase variable voltage variable frequency is provided to motor using a three phase SCR bridge. Eighteen SCR's and Six diodes.

Battery—14 automotive grade lead acid batteries connected in series. Each battery has a 44 amp/hour rating.

Top speed	55 mph
Total vehicle weight	2930 lb.
Acceleration time	0 to 30 mph in 10 s.

Stir-Lec I proved the technical feasibility of a Stirling engine—electric hybrid power train for a limited performance vehicle acceptable for city driving. This hybrid vehicle has the advantage that the heat engine can be of a smaller power rating required to operate the vehicle at steady speeds and peak power demands can be met by the battery-electric drive system.

V. GM512 Series Car [10], [11], [13]

In 1969, GM produced some special purpose urban electric cars. These were small vehicle designs. There were two versions, one was pure electric and the other was hybrid. These two passenger vehicles had an overall length of 86.3 inches and width of 56 inches. The cutaway view of a series 512 car is shown in Fig. 4.

The electric version had seven light weight 85 amp/hour lead-acid batteries. The nominal battery voltage was 72 volts with an additional 12-volt accessory battery. The vehicle used an SCR controlled dc-dc chopper and a Delco Remy dc series-wound motor, capable of producing 8.5 HP. The range varied from 5.2 miles at 30 mph to 9 miles at 10 mph. The top speed was 45 mph. The 115 volt ac outlet was used to recharge the battery.

The 512 hybrid version had the same propulsion system as that of the electric version. Electric drive was used from zero to 10 mph. At speeds of 10–13 mph, both electric and gasoline engine operated together. At speeds greater than 13 mph, the gasoline engine was used exclusively. The gasoline engine was 2 cylinder, 11.7 cubic inch (195 cc) displacement variety. A 90 volt, 20 amp alternator was belt-driven at engine speed to recharge the battery. The constant speed fuel economy was 45 to 50 miles per gallon. The top speed was 40 mph. The electric version was faster in acceleration than the hybrid version.

VI. GM's At & T Van [15]

In 1979, GMC Truck and Coach Division supplied 35 electric powered vans to AT & T for field testing. The

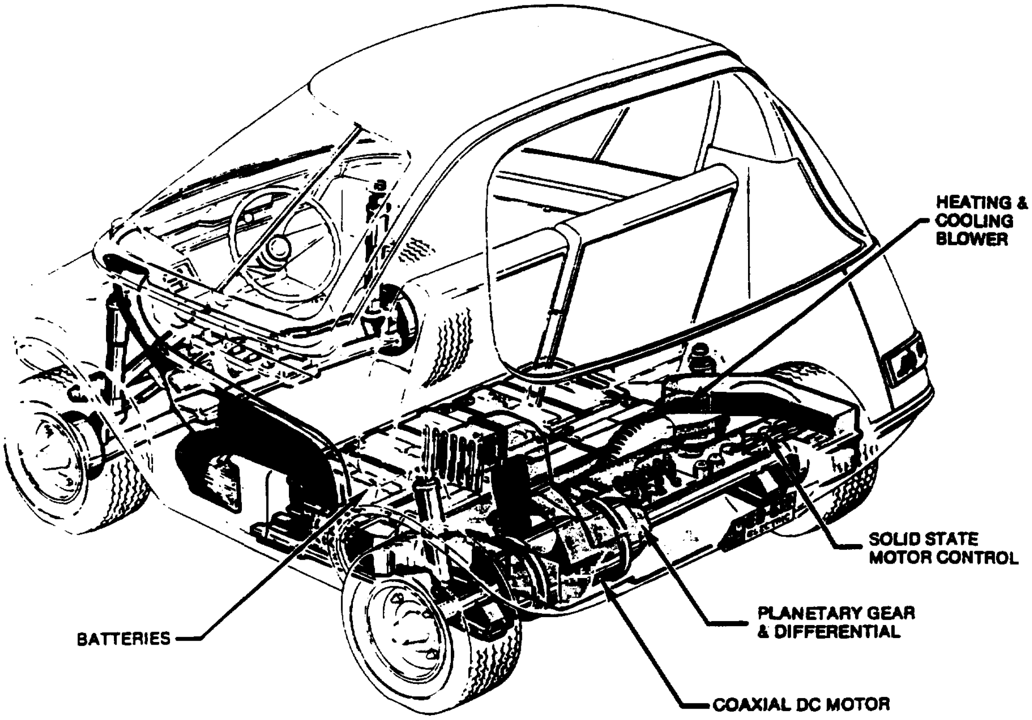

Fig. 4. Cutaway view of a Series 512 Car.

vehicle chosen for conversion was a 110 inch short wheel base IC Engine standard van, widely used in the AT & T fleets.

Drive Motor—50 HP dc series motor. Maximum speed was 3250 rpm. Motor weight was 325 lbs and was forced air cooled.

Controller—Two thyristor dc–dc chopper with field reversing contactors for direction and regenerative braking control. Rated for a nominal 220 V dc at 600 A and the operating mode was variable frequency, variable duty cycle over the range 0–300 Hz.

Battery pack—Lead-acid battery with wrought calcium lead grids and a special paste formation for deep cycling. Nominal voltage was 216 volts, obtained using two series strings of eighteen 12 V modules in parallel (totally 36 batteries). The weight of each battery module was 65 lb and capable of delivering 76 Ah at a 25 A rate. The pack was capable of delivering 33 KWh at a pack discharge rate of 50 A. Battery pack weight was 2575 lb.

Range	40 miles
Acceleration	0–30 mph in 12 s.
Top speed	50 mph
Gross vehicle weight	8100 lb
Brakes	Vacuum power assist hydraulic with full electrical regeneration.

Twenty vans were located with Pacific Telephone in Culver City and 15 vans were located with Michigan Bell Telephone in Detroit. The daily average mileage for Culver city vans was 14 miles for those in Detroit was 22 miles. At the end of the program, about 300, 000 van miles were accumulated. It was observed that driver habits, terrain, and charge techniques can affect the energy costs by about 20%. Regeneration feature resulted in 12% energy savings. The vehicle had limited range, heavy battery pack and costly components and materials.

VII. Electrovette [16]–[18]

Between 1970 and 1980, GM engineers have worked on different versions of the electric vehicles based on dc motors and SCR choppers. In 1970's, Chevrolet division developed Electrovette, based on Chevette powered by twenty 12 volt lead acid batteries. In 1979, these batteries were replaced by longer life nickel-zinc batteries. This program went through several stages of development. A cutaway view of Electrovette is shown in Fig. 5.

Motor—Separately excited dc motor; base speed of 2400 rpm (field weakening from 2400 rpm to 7000 rpm) (7000 rpm corresponds to 62 mph) continuous power was 17 KW; intermittent peak power of 25 KW; maximum torque 75 Nm; mass 80 Kg.

Propulsion battery—nickel-zinc, 120 V; number of cells 72; capacity 150 amp/hour; energy 17.3 KWH; Weight 334 kg; auxiliary battery 8 cell, 14 V nickel-zinc.

Power converter—The converter for controlling the armature of the propulsion motor was based on SCR chopper.

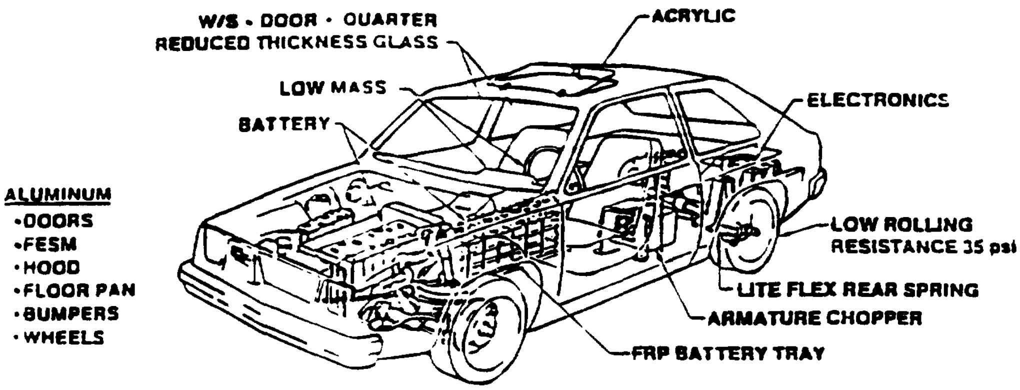

Fig. 5. Cutaway view of General Motors Electrovette.

The chopper frequency was 1000 Hz and duty cycle was varied to control the armature voltage. The field of the motor was controlled using power transistor bidirectional chopper at 1000 Hz. The control electronics for the motor and the total propulsion control was based on Motorola MC6800 microprocessor.

Transmission—2 speed electronic shift; mass 25 Kg.

Battery charging—The propulsion battery was charged by two separate methods. One was using the off board Home Base Charger and the other was On Board Charger based on Resonant Converter at 9 KHz resonant frequency. The On Board Charger was designed to simultaneously charge the propulsion battery and the auxiliary battery. During the normal driving, the unit reconfigured such that the auxiliary battery pack was charged from the propulsion battery. The chargers had the ability to charge the battery pack from 110 volts, 208 volts, or 240 volts ac.

Range	60 miles (EPA urban), 80 miles (at constant speed of 45 mph)
Acceleration	0–30 mph in 8.3 s., 25–55 mph in 19.8 s., 0–55 mph in 27 s.
Top speed	60 mph
Gradeability	27%

The Electrovette was not a representative of a production prototype vehicle. The main idea was to prove the applicability of Nickel-Zinc batteries for electric propulsion applications. As a result of this program, a significant amount of experience and capability was developed to effectively evaluate battery technology in a vehicle environment. Exceptionally good reliability of the Ni-Zn battery pack was demonstrated over approximately 35,500 miles of on-the-road testing. In 12 months of testing, the vehicles have shown themselves to be safe, reliable and sufficient road worthy for everyday use.

VIII. Impact [19], [20]

In January 1990, General Motors announced the first production intent electric vehicle called IMPACT. The Impact prototype is powered by two induction motors, one driving each front wheel. The battery pack consists of 32 compact 10-volt Delco Remy lead-acid batteries, connected in series. The inverter for converting the battery voltage to ac has 288 MOSFETs, each leg consisting of 24 parallel connected devices, switching at about 20 KHz. The slip frequency of the ac current is varied to maintain the highest possible efficiency throughout the rpm range. Each motor's output is transmitted to the tires via a 10.5 : 1 planetary gear unit.

Motor Type	Three phase induction motor
Max. motor output	57 bhp@6600 rpm (per motor)
Motor speed	9500 rpm (@60 mph)
Top speed	100 mph (rev limited to 75 mph)
Torque	47 lb/ft @0 to 6600 rpm (per motor)
Inverter type	Dual MOSFET inverter, frequency range 0–500 Hz
Battery type	Lead acid, 32 ten volt batteries in series
Capacity	42.5 amp/hour, 13.6 KWh
Battery weight	395 Kg
Battery charger	Integral with dual inverter package
Recharge time	2 h (80%)
Range	120 miles @55 mph
Acceleration	8 s (0 to 60 mph)
Vehicle weight	1000 Kg

GM's Impact demonstrated that the technology for propulsion components is now available to produce practical electric vehicles that may be competitive with today's gasoline powered cars in performance and cost. GM's Impact is the first production intent EV announced by a major car manufacturer. GM is planning to produce the advanced version of the IMPACT in late 1990's. The production version is likely to have better performance and more features.

IX. Impact 3 [22], [23]

In spring 1993, General Motors completed production of 12 engineering development vehicles, based on the 1990 Impact show car. These vehicles are being tested to ensure that they meet customer requirements and safety standards. The vehicle is an energy efficient 2-passenger, 2-door coupe like the original Impact and is designed to comply with all the vehicle standards which would make it "street legal" and safe. The Impact 3 is powered by a single induction motor of 137 HP. The battery pack consists of 26 compact 12-volt Delco Remy lead-acid batteries, connected in series. The inverter for converting the battery voltage is based on IGBT power devices.

Motor type	Three phase induction motor
Max. motor output	137 bhp @6600 rpm
Top speed	75 mph (electronically regulated)
Inverter type	IGBT based power unit
Battery type	Lead acid, 26 twelve volt batteries in series
Battery capacity	16.8 KWH maintenance-free lead-acid battery pack—312 V
Battery weight	395 Kg
Battery charger	Inductively coupled charging system
Recharge Time	2 to 3 h (80%)
Range (at 80%depth of discharge)	90 miles highway.
Acceleration	8.5 s (0 to 60 mph)
Curb weight	1323 Kg
Additional Features	electro-hydraulic power steering; electro-hydraulic braking system; blended regenerative braking; low inflation tire monitor; high-voltage isolation assurance; dual air bags; anti-lock power brakes; traction control; cruise control; power windows and power door locks; and solar reflective windshield and electric heat pump

The 12 vehicles built were subjected to same tests as GM uses to test its conventional cars. The vehicles were tested for braking ability, handling, crash protection, climate control, and several other factors.

In fall of 1993, GM started production of 50 vehicles for evaluation by 1000 potential customers of electric vehicles. The experience and information gained from this program will help GM to mass produce electric vehicles.

X. Electric Shuttle Bus [24]

In March 1993, Delco Remy and Allison Transmission divisions of General Motors have produced a prototype of 22 ft electric shuttle bus with the following specifications.

Motor	Two 3 phase 70 KW induction motors with integrated gear reduction
Battery	312 V maintenance free lad acid, 104 amp hour, 2 packs, 1000 pounds each.
Inverter	IGBT based inverter and microprocessor based control system
Acceleration	0 to 30 mph in 11 s
Maximum speed	50 mph
All electric range	30 miles with an optional range extender using internal combustion engine
Vehicle	22 ft length, 22 passengers, and gross vehicle weight of 14,000 lbs

This Electric Shuttle Bus is a demonstration vehicle. Based on the experience gained, Delco Remy and Allison Transmission are planning to commercialize these vehicles.

Conlcusions and Recommendations

In addition to the above mentioned electric and hybrid vehicles, there were many other experimental projects demonstrated by GM. Some of those projects were TS-14 electric hybrid Scraper [14], XEP-1 dual battery all electric vehicle, HX3 and Freedom Hybrid Vehicles based on 1990 Chevrolet Lumina APV [25].

Propulsion system development for future EV's will be focused on five areas: (1) vehicle range, (2) vehicle cost, (3) battery pack replacement cost, (4) battery pack life, and (5) quick and easy recharging [21]. Except for vehicle cost, this leads one to realize that most propulsion system development work will be on battery systems. The manufacturers of lead-acid batteries for EVs will have to meet the challenges of improving energy, cost, and life. For the next several years, the lead-acid battery will continue to be the one providing higher performance at lower cost. If EVs are going to gain greater acceptance by the public, battery developers must see that the battery packs have a minimum power of 400 W/Kg, energy of 200 Wh/Kg, life cycle of 2500 at a cost of about $75/KW, and be capable of being charged from 40% to 80% in less than 30 min. The application of Nickel Metal Hydride and Lithium Polymer batteries for EV applications have to be investigated.

Motor and inverter developers will need to focus their development into two major areas, efficiency improvement to increase the vehicle range, and cost reduction to help lower vehicle cost. Although PM motors and synchronous reluctance motors seem to be more promising, induction motors shall be continued to be used in EV applications in the near future. More emphasis may have to be given in obtaining higher torque per ampere capability and obtaining peak power performace without saturating the motor. Elimination of the speed sensors for induction motors or position sensors for PM motors would enhance the reliability of the propulsion system.

Advanced IGBT devices provide the best on-state and switching characteristics up to 20 KHz operation. When MCT's are commercially available, they are likely to replace the IGBT's. Resonant dc link inverters would provide almost zero switching losses, hence higher efficiency. They also would help to reduce the output dv/dt of the converter and the EMI generated. However, further research and development work is needed before they are used in EV applications.

The vector control of ac motors would give the best transient and steady state performance both in constant torque and constant horsepower region. Rated torque could be obtained down to zero speed. Smooth operation during regeneration could be achieved. The optimum PWM strategy in terms of digital implementation and harmonic reduction would be the space vector PWM technique. The entire propulsion system logic could be in an ASIC or on a small PCB.

The battery, inverter, and the motor together should be treated like one system. For the best performance and highest efficiency, these three units should be optimized as a system rather than separately designing and optimizing the individual units. The characteristics of all these three units have to be matched together to get the optimal accelerations, braking, maneuvering, heating and cooling of the system. In order to reduce the losses in the cables, the three units have to be located close to each other and the cables have to be properly routed to reduce the electrical interference.

Continuing worldwide R & D by consortia, private industry, academia, governments will advance these technologies further, making EV's even more viable. All-electric vehicles will be joined by hybrid electric vehicles to serve a broader segment of the transportation market. We should see many more EV's using modern propulsion system technologies into the market in the 1990's.

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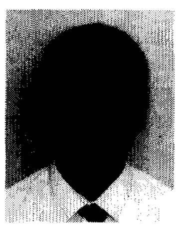

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