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INVESTIGATION OF THE FEASIBILITY OF A DUAL MODE ELECTRIC TRANSPORTATION SYSTEM

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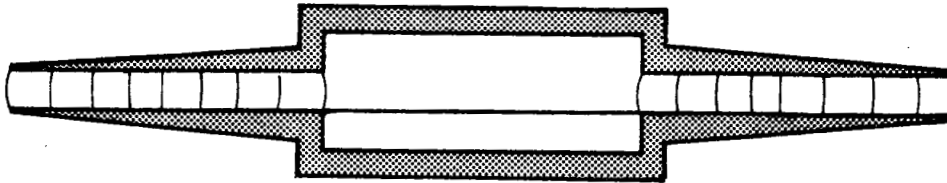
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Investigation of the Feasibility of a Dual Mode Electric Transportation System



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John G. Bolger
and
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- J. G. Bolger--report synthesis, impact analyses, system and mechanical concepts
- J. M. Cox--power conditioner concepts and analyses
- Dr. Klaus Halbach--magnetic analysis, consultation
- F. A. Kirsten--electrical system analyses and overview
- L. S. Ng--magnetic and electrical circuit analyses
- Dr. D. T. Scalise--technical overview
- Ferd Voelker--electrical system analysis and power conditioner concepts.

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ABSTRACT

The study reported here explores the feasibility of a highway transportation system that electromagnetically transfers energy to vehicles from powered roadways for high-speed or long-range travel, and uses energy stored in the vehicles for other travel.

The energy coupling between roadway and vehicle is functionally similar to a transformer. The roadway energy source is imbedded flush with the roadway surface. When vehicle's energy pickups are suspended over the source, energy is magnetically coupled through the clearance gap between source and pickup.

Analyses and modeling indicated that adequate power can be efficiently coupled by the system. The economics of the system appear to be favorable, and no implementational problems were identified that would make the system impractical.

In addition to the engineering development of the power system, including performance verification with prototype hardware, continuing efforts should further address the effects of stray magnetic fields, the compatibility of the system with existing automobiles, electrical safety, and the process of transition from the use of existing automobiles.

SUMMARY

GENERAL

This report addresses a wide range of factors that could affect the feasibility of a new highway transportation technology. Central to the new technology is a means of coupling power to electric vehicles without physical contact as they travel on freeways or urban arterials. Vehicles will also carry stored energy for use while off the system, hence the system is referred to as a 'Dual Mode Electric Transportation System' (DMET).

The foundation of the investigations reported here includes evolutionary engineering investigations of the concept, magnetic and electrical circuit parametric and performance analyses, and 1/25th scale power coupling and operational models. The total funded effort, which began in 1976, was less than two man years; the preceding unfunded concept development, which included concept development and modeling, involved a greater effort and time span.

The reported investigations encompass a broad range of considerations, hence are typically less than exhaustive treatments. The attempt is made to identify areas of major concern to the evolution of this new technology and to assure that there exists at least one potentially practical solution to each. The methodology used to investigate technical concerns was to outline the performance requirements of system components and then make a specific design study to assess the difficulty of meeting those requirements.

The investigations also include impact analyses, which draw upon the work of other investigators of electric vehicles to provide a basis for comparison. The analyses are based primarily on data for the Los Angeles area. These data also provide the basis for the postulated implementational sequence that was used to assess the magnitude of that process.

DESCRIPTION

The DMET system's major components are the roadway power source, way-side power conditioners, and electric vehicles, which carry both stored energy (battery or flywheel) and a power pickup. The roadway power source

is a continuous strip installed flush with the road surface in the center of the powered lane. The source is approximately 2 feet wide and 3 inches deep. It is comprised of a laminated sheet steel 'core,' which surrounds a single electrical conductor on each side and from below. The conductor is protected from above by thick, tough insulation. It carries an alternating electric current to induce magnetic flux to flow through the core of vehicles' power pickups, which are suspended above it and thus couple energy much as does a transformer. The magnetic flux path can include clearance gaps that exceed 1 inch and can tolerate substantial guidance (steering) errors. The magnetic field of the source can provide guidance to vehicles and can be used to transmit data to them.

Wayside power conditioners convert utility system power to the higher frequency needed by the DMET system. The conditioners are installed adjacent to the powered roads at intervals exceeding 1 mile.

Vehicles can be similar to conventional cars in both size, comfort, and performance. The freeway power source can provide all the power needed for high-speed travel, as well as for battery or flywheel recharging. The battery or flywheel is required only to meet the energy demands of street travel, which is of relatively short range and modest speed, and passing or lane changing on freeways.

PURPOSES OF THE CONCEPT

The incentive to develop the system are several. The system is electrical, hence can utilize energy from any practical source. It provides the potential for powering trucks and buses as well as automobiles, and can be designed to be more efficient than other vehicle power systems. The DMET system is amenable to the inclusion of automatic vehicle controls, which is the most feasible means of achieving large increases in the capacity of urban freeways. Because the public has demonstrated a strong preference for individual automotive transportation over mass transit systems, and a reluctance to countenance the construction of new freeways, increasing the capacity of existing freeways will become increasingly important.

DESIGN STUDY RESULTS

The investigations of design considerations and the subsequent design study provided the following conclusions:

- The power required for dense traffic loads can be supplied by the system.
- It is necessary to equip only a limited number of routes with the roadway power system in order to provide area-wide service with DMET vehicles.
- Losses in the system are small, so that the daily average efficiency is high.
- Physical clearances of the order of 1 inch are required between the power pickup and the road. The power coupling can be designed to operate with that clearance.
- The power coupling requires careful, but not extremely precise, vehicle guidance or pickup positioning in order to couple the required amount of power.
- Economical power conditioners capable of meeting system power requirements can be produced by industrial manufacturers.

DEVELOPMENT TASKS

Continuing work should further address:

- Stray magnetic fields-- the intensity and alternating frequency of these fields should be reduced to practical minimums in order to reduce thermal effects on conventional vehicles, and interference with communications systems and electronic instruments.
- The optimization of roadway power system designs to provide the best balance between costs, performance, and efficiency.
- Source designs capable of withstanding the abuses of the roadway environment (abrasion, impacts, freezing, weathering, settling) with minimum maintenance. Failure modes that could compromise the electrical integrity of the insulation are of particular concern.

- Power conditioner control circuits that can sense electrical faults or abnormalities and interrupt the power circuit before damage could occur.
- The implications of the inclusion of automatic vehicle control systems in the DMET roadway power system. The early evaluation and development of automatic control systems is necessary to allow the inclusion of any special features in power source designs and to determine the increase in traffic capacity that automatic controls will provide.
- The quality of vehicle guidance that will occur naturally when DMET power sources are present in roadway lanes, and the possible alternative use of automatic vehicle steering or pickup positioning systems.

SYSTEM IMPACTS AND COMPARISONS

A DMET vehicle was characterized using methods similar to those of other investigators of electric vehicles. The characterization was then used to compare the impacts of its implementation with those of alternate non-petroleum based vehicle technologies. Significant findings included:

- The energy consumption of the DMET vehicle would be less than the alternative vehicles.
- The purchase price of the DMET vehicle would be higher than an automobile with a conventional internal combustion engine (ICE), which could use synthetic fuel, but would be less than a battery-powered vehicle.
- The operating cost of the DMET vehicle would be slightly less than that of the ICE vehicle and significantly less than battery-powered vehicles or guideway dual-mode systems.
- The amortization of the capital cost of the roadway power system is a very small component of DMET vehicle operating costs.
- The most significant manufacturing requirements during the construction of a national DMET system would include those for transformers and capacitors. The requirements were estimated to be 12% and 245%, respectively, of the 1974 annual production rates of these items.

- The increase in peak power demand due to the addition of a comprehensive DMET system in Los Angeles was estimated to be only 4% of the peak demand that would otherwise occur.
- Power is available to freeways at many closely spaced locations in both the San Francisco and Los Angeles areas, which were the subject of investigation.
- The cost per vehicle of major infrastructure additions were least for supplying synthetic fuel for ICE automobiles, somewhat higher for the DMET vehicles, and highest for battery-powered and guideway dual-mode cars.

IMPLEMENTATION

The magnitude of a DMET implementation program for a metropolitan area was investigated by hypothesizing the construction of a DMET power system network in the Los Angeles basin. The construction program was patterned after the history of the freeway construction program from the 1950s to the 1970s. The construction of the required 5463 lane miles (which would be reduced if automatic control systems were added) was projected in a 16-year period. The total construction cost would approximate 2.4 billion dollars, with a peak capital spending rate of 228 million dollars in the tenth year of program.

The implementation process should be studied in depth. A site-specific study that addresses the full range of necessary planning decisions should be undertaken. Issues that should be addressed include:

- The choice of routes to be equipped with power systems, and the number and schedule of construction of powered lanes on those routes.
- The choice of lanes to be powered on the chosen routes.
- Regulations required, if any, for the use of powered lanes by ICE autos.
- The desirability of providing DMET bus service on powered routes.

- The financial process for DMET systems, including the acquisition and allocation of construction funds, the acquisition and disbursement of cost amortizing, and operating and maintenance funds.
- The cost/benefit aspects of automatic control systems.
- The establishment and management of power system maintenance and power billing functions.

1. Introduction

1.1. THE PROBLEM

Transportation of people is one of the major activities in the United States; 13% of the gross national product is devoted to passenger travel. The huge expenditures that have been made have been responsible for achieving personal mobility, which has shaped our cities and our way of life.

Existing personal transportation systems have evolved from a succession of technologies, some of which are shown in Table 1.1. The surviving urban public transit technologies--street cars, busses, and rail rapid transit, contribute only 5% of travel in urban areas. The automobile supplies the remaining 95%.¹

The facilities that make up the automotive system, i.e., cars, streets, freeways, parking, garages, and service stations, are extensive and widely used. The developed routes are exactly matched to the structures and needs of commerce and the public. It is almost inconceivable that a new major transportation system could supplant the automobile in the foreseeable future without making use of a major share of the fixed facilities that now exist.

The transportation service being supplied by the ICE automobile/roadway system has several serious deficiencies. These deficiencies are mostly below a threshold that would induce vigorous public pressure for change:

- The present easy availability of gasoline masks the shortages and increasing prices that will soon occur. The accompanying critically unfavorable balance of payments caused by petroleum imports is a problem that is not directly perceived by the general public.
- A very large and costly program has been devoted to reducing ICE emissions. The costs have included R&D, control devices, and increased specific fuel consumption. The result of this program was a net reduction in vehicular emissions of only 9% from 1970 through 1974.² Increasingly stringent emission standards are dictating automobile design changes that are not always fully developed and typically increase costs to the consumer.

Table 1.1. Major U. S. Urban/Suburban Personal Transportation Technologies.

Technology	Maximum Usage					Incentive to Implement
	Year	Route Miles	(km)	Vehicles	Passengers/Year	
^a Horse-drawn cars	~1881	3,000	(4,800)	18,000	188×10 ⁶	First available system
^a Cable cars	~1890	662	(1,065)	5,000	400×10 ⁶	Speed, operating cost
^a Electric street cars	1918	26,000	(42,000)	60,000	11,000×10 ⁶	Speed, cleanliness, reliability
^b ICE buses	1945	90,000	(145,000)	50,000	9,900×10 ⁶	Low capital, operating costs
^b Rail-rapid transit	1945	1,223	(1,968)	10,000	2,700×10 ⁶	Capacity, speed
Urban ICE automobiles*	?	420,000 ^c	(676,000)	63,000,000 (est.)	44,000×10 ⁶ (est.)	Trip time, comfort, convenience, flexibility

* In cities over 100,000 population; 1972.

Source: a W. D. Middleton, "Rail Transit and the Building of the American City," Railw. Age 7/4/76.

b ATA Transit Fact Book.

c 1974 National Transportation Report (DOT).

- Arterial roads are increasingly overloaded; yet the public is not inclined to support the construction of new roads. The public has become concerned with residential and commercial dislocations and the environmental costs involved.
- Approximately 50,000 people in the U. S. continue to lose their lives in traffic accidents each year.
- Adequate public transportation is not available to many who do not have access to an automobile.

1.2. REQUIREMENTS FOR SOLUTIONS

If one were to postulate a transportation system that offered a comprehensive solution to the problem set, the following characteristics would probably be required:

- A. It would be widely accepted and used by the public. This would require that it be fast, comfortable, flexible, and cost effective.
- B. It would make maximum use of existing routes and facilities.
- C. It could use energy from any significant future source, and would use it frugally.
- D. It would be environmentally benign.
- E. It would incorporate public as well as private transit.
- F. It would assign costs equitably.
- G. It would provide high passenger-carrying capacity per route with improved safety.
- H. It would utilize materials that are in adequate supply, and technology capable of being developed in the near future.

The feasibility of the dual-mode electric transportation system (DMET) is the subject of this report. An assessment of the system with respect to characteristics A-H will provide an insight into its potential.

A. Table 1.2 shows how various options in urban transportation systems and the DMET system might fare in such an assessment. The automobile has demonstrated widespread acceptability, while the public transit systems have attracted a very limited patronage in urban use. The DMET system might provide a service very similar to ICE automobiles, i.e., range, speed, and comfort. Hence, it is credited with the

Table 1.2. Assessment of the Potential of Urban Transportation Systems

	Desired Characteristics							
	A*	B	C	D	E	F	G	H
Urban Transportation Technology	Acceptability	Use of Existing Routes, Facilities	Energy Availability and Economy	Environmentally Benign	Private and Public Transit	Cost Assignment	Passenger-Carrying Capacity & Safety	Material and Technology Availability
ICE Auto/Roads	x	x	o	o	x ^a	o	o	x
Diesel Bus	o	x	o	o	o	x	x	x
Rapid Rail Light Rail Automated Guideway	o	o	x	x	o	o	x	x
DMET	p	x	x	x	x ^b	x	p	p

x = criterion met

o = criterion not met

p = criterion possible, requires investigation

^a Assumes availability of jitney service in conjunction with bus.

^b Assumes jitney service and/or DMET buses.

* Refers to characteristics, p. 3.

possibility of being widely accepted. This would not be the case with electric vehicles with only battery power because of their limited range and performance.

B. In order to provide a major share of passenger miles, rail transit (guideway) systems would require a very large expansion of routes and facilities. Buses and DMET vehicles could make use of the existing roads that are now used largely by ICE vehicles.

C. The electric power systems of DMET and rail transit systems provide multifuel capacity. The diesel buses and ICE automobiles are, and will continue to be, dependent on petroleum or synthetic petroleum substitutes.

D. Adverse environmental impacts of the electric transit systems are generally much less than those of the urban automobile. The emission of sulfur dioxide by electric generating plants is the only significant concern. Thus, all the electric systems are indicated as having met environmental criteria.

E. Public transit could be made available on each of the transit technologies, assuming the use of taxis or jitneys on highways. Private transit of course would not be available in public transit systems.

F. Transportation system costs are not equitably assigned to automobile users or to transit riders. The cost of freeways, parking facilities, and environmental degradations would be difficult to fully distribute to automobile users. The operating and capital costs of rail urban transit systems are only partially met by the systems users. Attempts to increase fares to meet costs in transit systems would cause undesirable modal shifts. Some bus systems are able to meet their operating costs from the farebox, so Table 1.2 indicates that the criteria of cost assignment could be met in this case. In the case of DMET systems, the ability to meter the power used by a vehicle provides an equitable basis for billing the system's costs to the user. Larger vehicles that use large amounts of power would be billed accordingly. Capital costs could be included in this billing.

G. Automotive transportation is increasingly congested and demonstrates a relatively high accident rate. The automotive system is thus indicated in Table 1.2 as not having met the criteria of safely providing high passenger-carrying capacity. The diesel bus could markedly improve the passenger-carrying capacity of a given route, and do so with a reduced rate of injuries, as could the rail/guideway systems. The DMET system is adaptable to automatic controls, which may incorporate numerous safety features similar to automated rapid rail-transit systems. The passenger-carrying capacity of automated highway systems can be much greater than for individually controlled vehicles. Hence the DMET system is credited with the possibility of meeting this criteria.

H. Materials (except for fuels) and technology are available for the construction of all the existing systems. It will be shown that the material requirements of the DMET system can be met from existing sources of supply. No technology requirements beyond the state of the art have been identified, so the DMET system is credited with the possibility of meeting this criteria.

The development of the dual-mode electric transportation system is in an early phase; therefore, some assessments are shown as "possible." It is one of the main functions of this report to make a preliminary judgment as to the strength of these possibilities in view of available information. The readers are encouraged to make their own assessments of the DMET system with respect to these criteria after considering the subject matter that follows.

1.3. PHILOSOPHY OF THE DMET CONCEPT

The origin of the DMET concept was stimulated by concern for rapidly worsening air pollution in the late 1960's. The logic of the concept was simple: The system could be designed to be highly efficient; thus would use much less energy. The electrical energy could be supplied by power generating plants located to minimize emissions in urban areas.

The concept would inductively couple electric power to vehicles as they traveled on arterial routes at high speeds. Vehicles would

also carry stored energy in a battery pack or flywheels, which would allow them to travel limited distances at lower speeds on city and suburban streets. Vehicles would not be mechanically constrained on powered roads--their supply of stored energy would allow them to pass other vehicles or change lanes. Roadway power would recharge the stored energy supply while the vehicle traveled on powered roads, thus greatly reducing the amount of storage required for typical urban driving cycles. This would also avoid the need for high-capacity charging facilities in residential garages.

Networks of roadway power systems would be implemented gradually. First, a power system on a high-density corridor would be constructed, which would meet the commuting needs of a large number of users who lived and worked within a distance of 10-15 miles (16-24 km) of the corridor. The system would then be gradually lengthened and other arterial routes added until a comprehensive network was established. The network would allow DMET vehicles to travel anywhere in the area, but would require a relatively small number of powered route miles. Parallel completion of networks in other metropolitan areas would eventually lead to the equipping of major intercity routes to provide full intrastate and interstate mobility.

As research into the concept advanced, concerns with regard to the excessive consumption of energy, especially petroleum, by automobiles assumed increasing importance. Energy conservation was fundamental to accomplishing the concept's original objectives, and the system, being electrical, could utilize energy from any known primary energy source.

Figure 1.1 shows how automotive issues change with time. This figure includes only issues concerning the automobile as a component of a system. Other issues relating to the automobile/roadway transportation system were outlined in Section 1.1. Several new characteristics peculiar to the DMET system appeared to offer significant potential for impacting the system's problems:

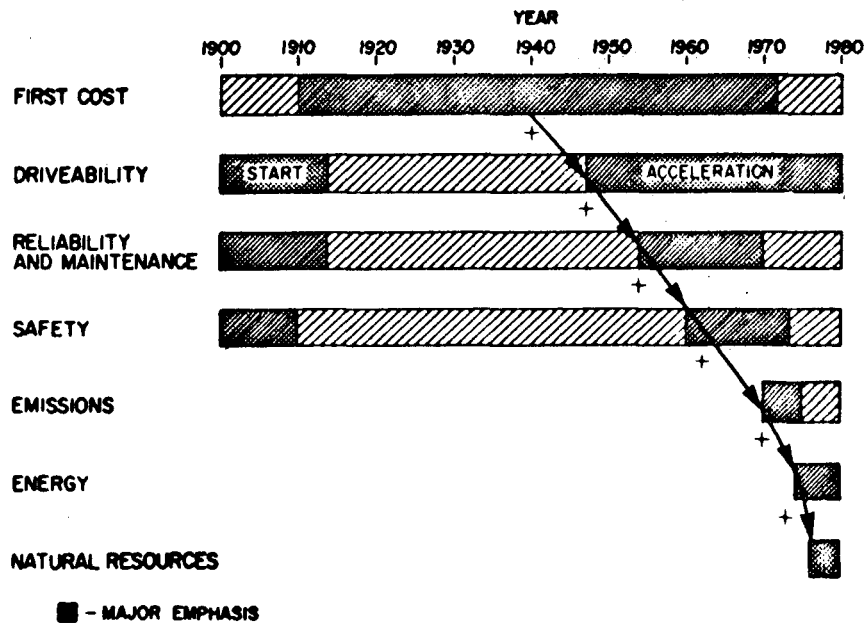


Fig. 1.1. Automotive issues as a function of time. (Source: B. Sternlicht and G. M. Thur, "Alternative Prime Movers for Future Automobiles," in Second Symposium on Low Pollution Power Systems Development, Document No. 2, November 1974). (XBL 774-735)

- The magnetic roadway power system might be used to improve traffic flow and safety by providing:
 - automatic vehicle guidance.
 - automatic vehicle spacing.
 - communications to vehicles regarding speed zones and locations.
- Energy and mileage use by the vehicles on the system could be metered. The data might be used to equitably assign to users the cost of power and/or the system facilities.
- The power system might support the energy needs of electric buses and trucks traveling at freeway speeds. Dual-mode electric buses might be an important new tool in providing environmentally acceptable transportation within central business districts.

1.4. OBJECTIVES AND SCOPE

The objective of this report is to make a preliminary assessment of the feasibility of the DMET concept. The underlying incentive to make the assessment is the potential of such a concept for saving energy and petroleum. This potential could never be realized, regardless of its technical efficacy, unless it was widely accepted and used. For that reason, this preliminary assessment is broad in scope and general in nature, encompassing operational, economic, resource consumption, environmental, and institutional considerations. A secondary objective of the work is to illuminate vital concerns that will require further study.

The report deals with a technology in its infancy. The analyses are based on preliminary engineering and research of very limited extent. Only the fundamental technical merits of the concept have been proved through engineering studies and with some physical modeling. The analyses that follow, then, sometimes involve large extrapolations of the present state of knowledge. The implications of this concept are so large that each one will be scrutinized in successively greater detail as the concept advances. This report represents a first snapshot of the technology from long range. Although many fine details may be obscure, the broad outline of the concept and its considerations should be clear.

1.5. ORGANIZATION OF THE REPORT

The report is designed to lead the reader from a general understanding of the nature and operation of the system's components, through a study that quantizes the cost and performance of a sample system design, to analyses of the impacts to be expected from the DMET system. Comparisons are then made to alternative automobile technologies, which are also capable of using energy other than from petroleum.

A description of the components of the system is provided in Section 2. An operational scenario is then developed for a DMET automobile in an urban driving cycle. The scenario is intended to illuminate characteristics that may influence the acceptability of the system to the user. The factors that determine the suitability of the DMET system to a particular application are then developed.

Section 3 deals with major engineering considerations involved with the design of a DMET system. The engineering of the system will involve many parametric tradeoffs. It is not the intent of this section to develop a methodology to optimize the tradeoffs, but only to identify the factors involved in processes. These identifications are useful to the assessment of the scope and difficulty of the R&D programs that lie ahead.

Section 4 presents the results of a design study of a DMET system. The study uses a system of arbitrarily chosen specifications to develop an internally consistent set of cost and performance data, and to confirm that at least one straightforward design solution exists for each major component.

In Section 5 impact analyses are presented. Several of these analyses are based upon an earlier EPA study of the potential impacts of battery-powered electric vehicles in Los Angeles. The analytical technique used here was to identify the differences between DMET vehicles and the battery-powered vehicles. The various impacts dealt within the EPA study were then adjusted accordingly. Some impacts on highway departments and electric utilities are peculiar to the DMET system, but we were able to use data from the EPA study as a basis for quantizing the impacts.

Comparisons are drawn in Section 6 between the DMET system and the alternative automotive technologies, which appear to offer the most promise for favorably impacting the national energy problem.

A postulated implementation sequence is developed in Section 7 to provide some perspective with regard to the construction programs, time scale, and financial commitments that could be involved in the implementation of the DMET system.

2. Description of the Dual-Mode Electric Transportation System

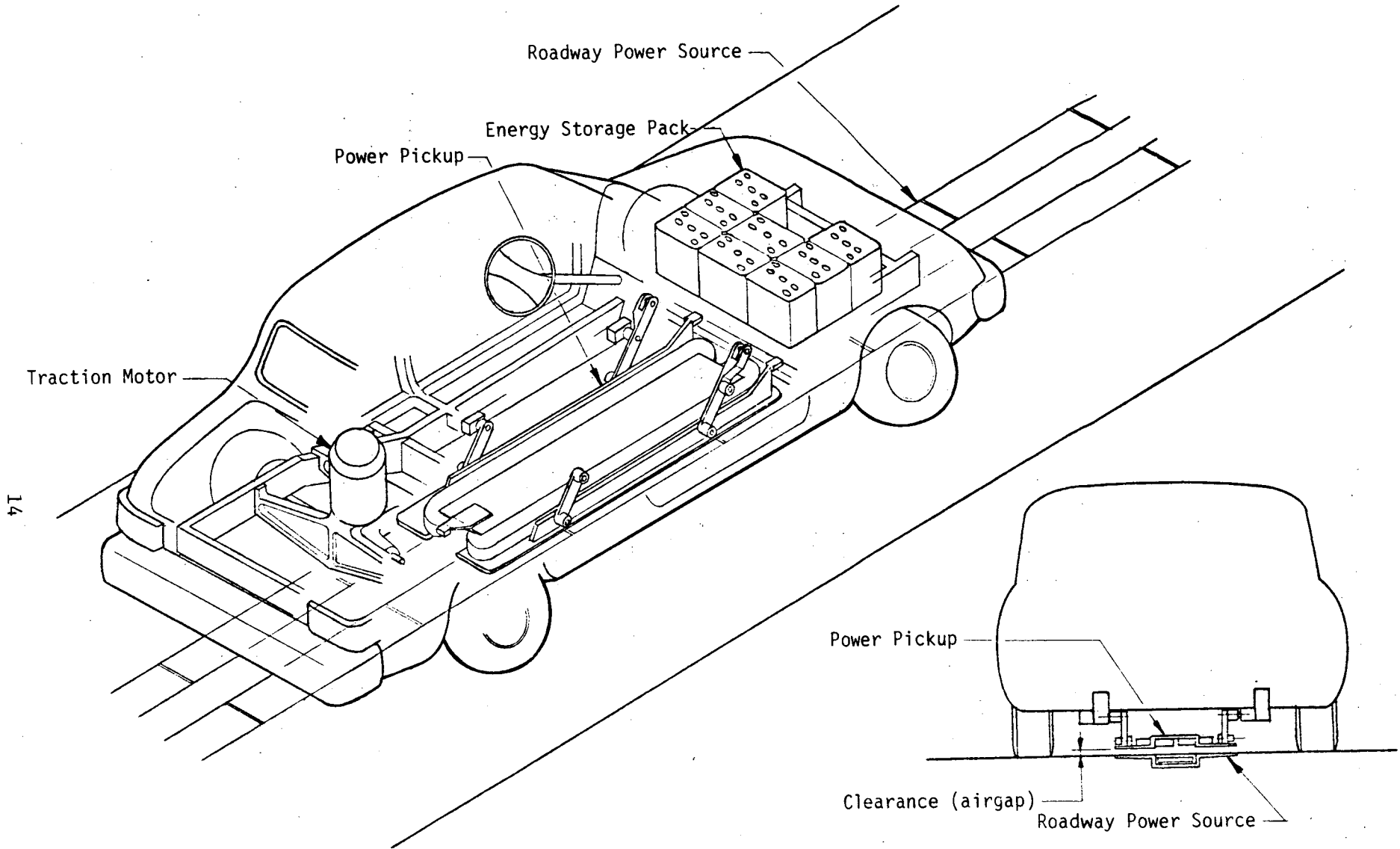
2.1. SYSTEM COMPONENTS

The system is based upon continuous electric power "sources" installed in the center of arterial roadway lanes with their upper surface flush with the roadway (see Fig. 2.1). The source is designed to provide power sufficient to propel vehicles at highway speeds, plus a reserve for charging a small energy storage pack (battery or flywheel) that vehicles will carry. Roadside power conditioners provide alternating current to a single, stranded conductor in the power sources. The conductor is enclosed on three sides by a laminated steel "core." The upper side is protected from the roadway traffic by a thick layer of tough insulating material.

Roadside power conditioners will provide current alternating at a frequency of the order of 180 Hz to the sources. Conditioners will be spaced so as to keep system voltages to levels consistent with the insulation design of the source. The voltage required is proportional to the length of source that is in the circuit. Preliminary work indicates that spacing of the order of 2 to 5 miles (3-8 km) between conditioners may be used. A schematic system diagram is shown in Fig. 2.2.

Vehicles carry a suspended power "pickup" with a core similar in cross section to that of the power source. The pickup is suspended over the source, completing the magnetic circuit through which flux is induced by the source current (see Fig. 2.3). A coil is wound around the central portion of the pickup core. The flux links the lower portion of the pickup winding and the source conductor; hence voltage is induced in the pickup coil, which can be used to power the vehicle. The power capacity of the pickup is proportional to its length. Small vehicles will require only a very short pickup, while large trucks and buses may require more than one pickup.

Pickups are suspended by mechanisms that can maintain relatively close control of the pickup's elevation while it is lowered over a source, and will raise the pickup to provide normal clearances under vehicles while they operate on city streets (see Fig. 2.4).



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Fig. 2.1. Roadway-power system for electrical vehicles. (XBL 774-736)

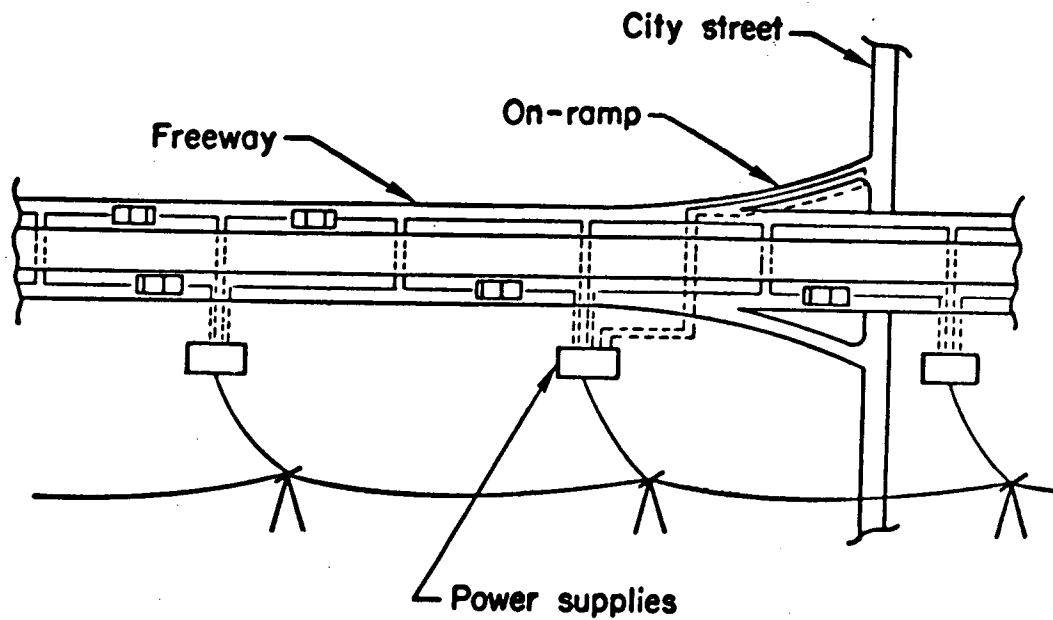


Fig. 2.2. Roadway power-system schematic. (XBL 774-737)

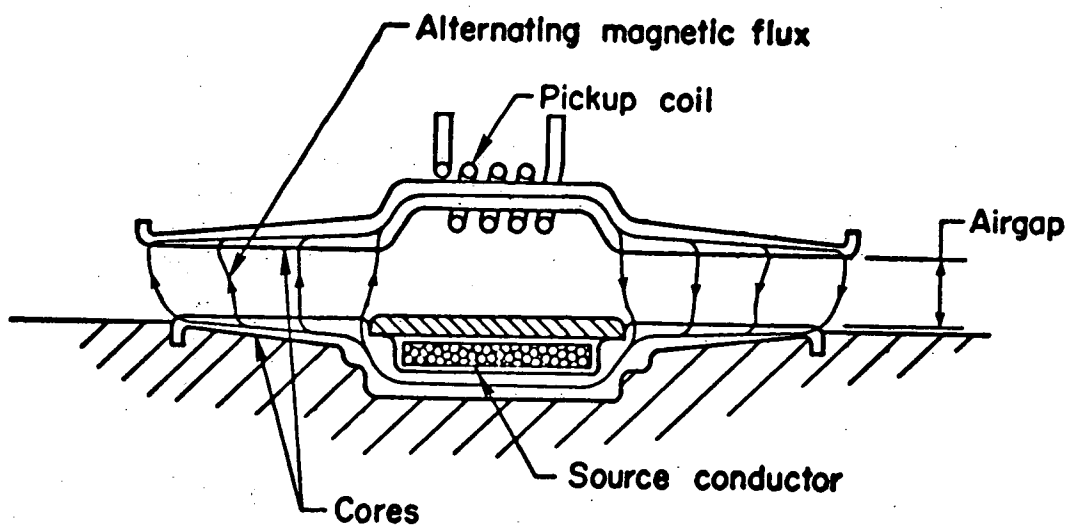


Fig. 2.3. Coupling schematic. (XBL 774-738)

Vehicles' power systems will include an electronic control system capable of continuously regulating the coupled energy being used to power the vehicle and/or charge the storage energy pack. The energy storage on board the vehicle serves as a "load leveler" capable of averaging effects of momentary variations or interruptions in coupled power. Variations in coupled voltage will result from continual small changes in the airgap and from guidance errors.

The size of the storage pack will be sufficient to allow vehicles to leave or enter powered lanes at freeway speeds, or to pass stalled vehicles. A stored energy pack of this power capability would also support approximately 25 miles (40 km) of travel at 35 mph (56 km/h) off the powered roadway.

Figure 2.5 shows power-train schematics for two types of roadway-powered vehicles. Figure 2.5(a) shows a stored energy/coupled power hybrid, where the energy flow can be:

1. Into the power coupling. The output is split between the the propulsion system and energy storage pack in proportions depending on the propulsion power requirement and the state of charge of the energy storage pack.
2. Out of the stored energy pack to the propulsion system.
3. Out of the propulsion system (regenerative braking), into the stored energy pack.

Figure 2.5(b) shows an IC engine/coupled power hybrid in which all propulsion energy is supplied in real time. This type of vehicle would be suited to the near-future needs of commuters whose vehicle usage requires frequent trips well outside the metropolitan area. The small engine would operate at high load (low specific fuel consumption) and would be used sparingly in the urban areas where it would contribute to air and noise pollution.

2.2. OPERATION OF THE SYSTEM

The velocity profile of an assumed operational scenario for a vehicle equipped for operation on the roadway power system is shown in Fig. 2.6. A description of the scenario follows:

The day started with the vehicle in the owner's garage where its energy storage pack had been fully charged during the night. The

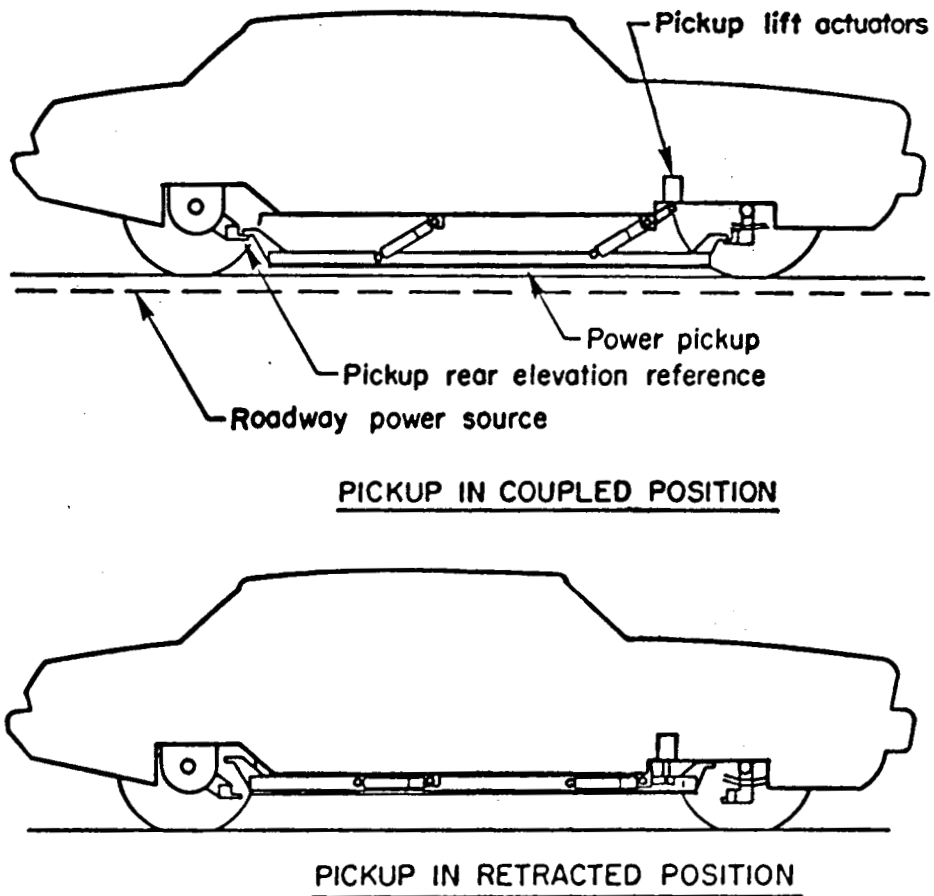


Fig. 2.4. Pickup suspension schematic. (XBL 774-739)

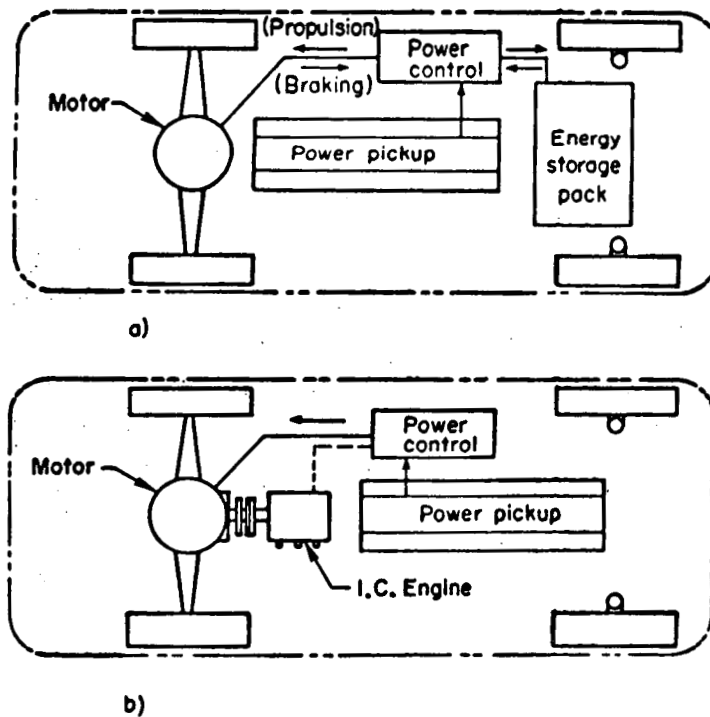


Fig. 2.5. Vehicle power-train schematic. (a) Roadway-powered car with stored energy pack; (b) roadway power with IC engine hybrid. (XBL 774-740)

charging was done automatically by parking the car over a small inductive power "source" on the garage floor. The car was a two-door five-passenger car with generous interior dimensions.

The car slipped quietly out of the garage without warmup and headed for the nearest freeway on-ramp, 5 miles away. Stop-and-go performance on city streets was similar to ICE cars--the result of a light vehicle and an electric power train that developed high torque at low speeds.

At the entrance to the freeway on-ramp, the driver operated a switch to lower the power pickup below the car. With power coupled from the source on the on-ramp, the vehicle accelerated to freeway speed and then blended into freeway traffic. The transition from on-ramp to freeway was accomplished on stored energy, although the driver would not have been aware of it except for the indication of discharge by an ammeter on the dash.

On the freeway, the ammeter indicated that the battery was being recharged, until a slow-moving truck that was occupying the powered lane had to be passed. The meter again indicated the use of stored energy as the car left the powered lane, passed, and re-entered the powered lane.

The car reached the desired off-ramp. The driver switched the pickup to "up" position and decelerated to a stop at the street intersection. The charge indicator showed that the storage pack was not fully charged; the 6-mile freeway trip at speeds up to 55 mph was not long enough to obtain a full recharge.

The driver reached his office, 4 miles from the freeway through stop-and-go traffic, and parked. The charge indicator then showed 72%, so there was no need to park in one of the charging spaces provided for electric vehicles that are used primarily for around-town service.

The cycle was reversed in the afternoon, and the car was garaged with 43% charge remaining.

An after-dinner round trip 2 hours later to a shopping center 18 miles away found the vehicle with 79% charge remaining when it was garaged for the night; it had been recharged on the freeway during the trip and in the garage during the dinner hours.

The scenario illustrated several important features of the system. The vehicle traveled 66 miles (106 km) during the day with a conventional energy pack weighing of the order of 500 pounds (227 kg), and finished its day 79% charged.

At no time was the energy pack operated at less than 43% charge; the life of the pack under these conditions would be longer than if it had been deeply discharged by battery-only operation. The energy system required no attention from the driver other than casual monitoring. Charging was automatic.

No restrictive driving procedures were involved; the car could enter and leave the highway, or pass at any time. The only unusual requirement was to raise and lower the power pickup.

The vehicle was able to provide good performance because of its relatively light weight and the availability of high power while traveling on freeways.

The vehicle would have used of the order of 20 kWh, which would have cost the driver 1¢ per mile.

Full freeway speeds could be maintained indefinitely, with power concurrently available for charging the energy storage pack.

The energy pack used was typical of those currently available. Advanced batteries or flywheels could reduce the pack weight, increase the vehicle's performance, and decrease its cost, but they are not a requirement of the functional and economic viability of near-future systems.

2.3. SUITABLE APPLICATIONS

A traffic characteristic that is important to the effectiveness of the roadway power system is the increasing concentration of travel on metropolitan freeways. This trend is shown in Fig. 2.7. California freeways accounted for 37% of all vehicle miles traveled in 1972, yet they represented only 2-1/2% of all California roads.³

Figures 2.8 and 2.9 illustrate how a relatively small number of powered roadway miles can provide an extensive electric automotive system. Figure 2.8 is a California Department of Transportation map that graphically portrays the distribution of traffic on state highways. The map clearly indicates the limited route mileage of high-traffic-

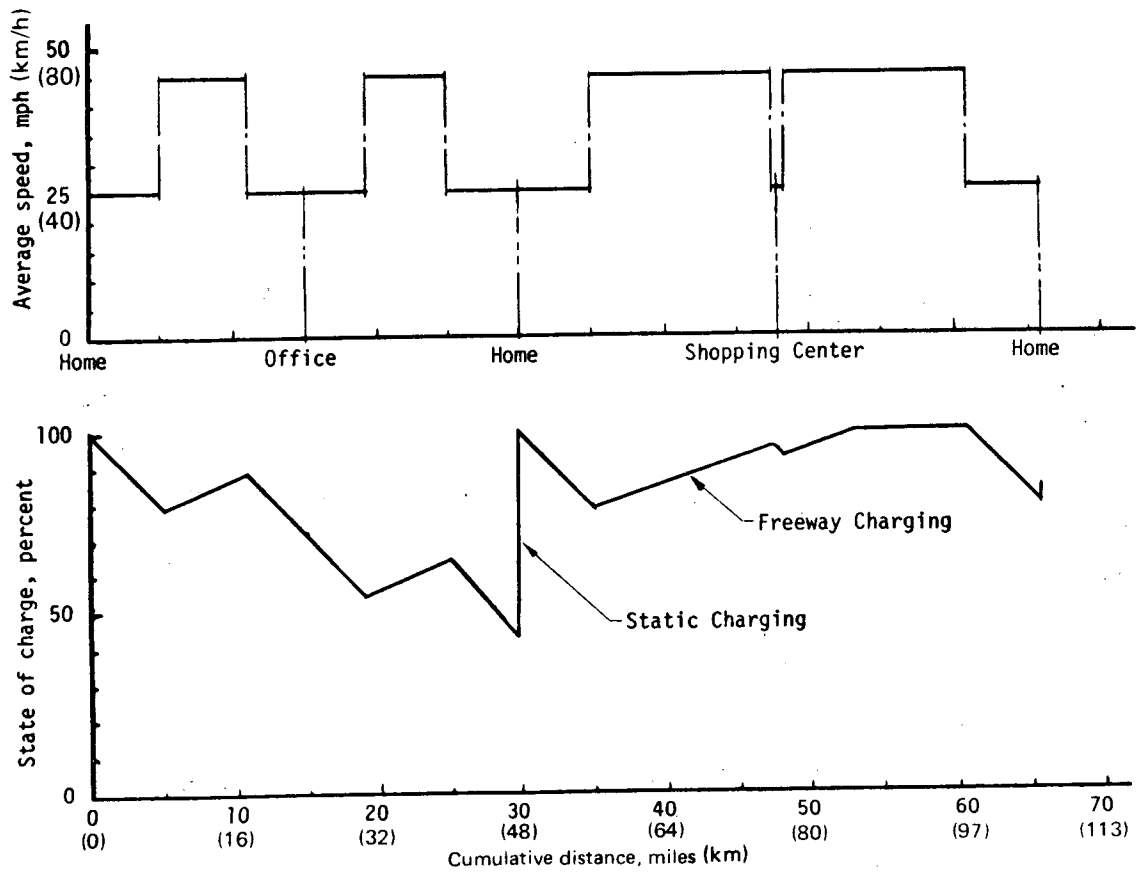


Fig. 2.6. Daily use scenario for a DMET vehicle. (XBL 774-741)

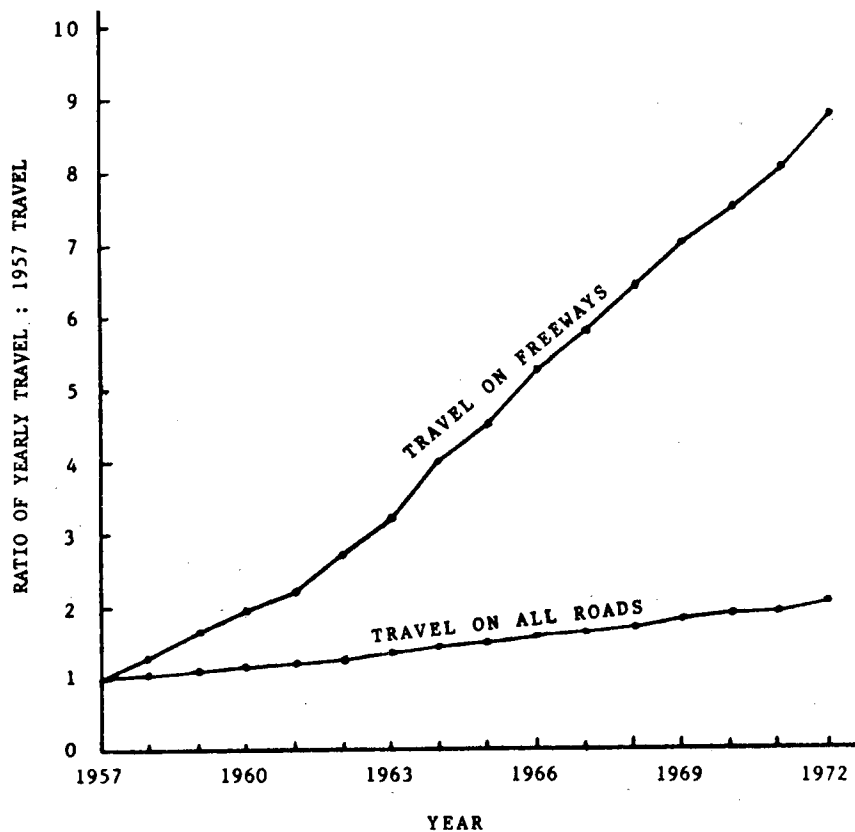
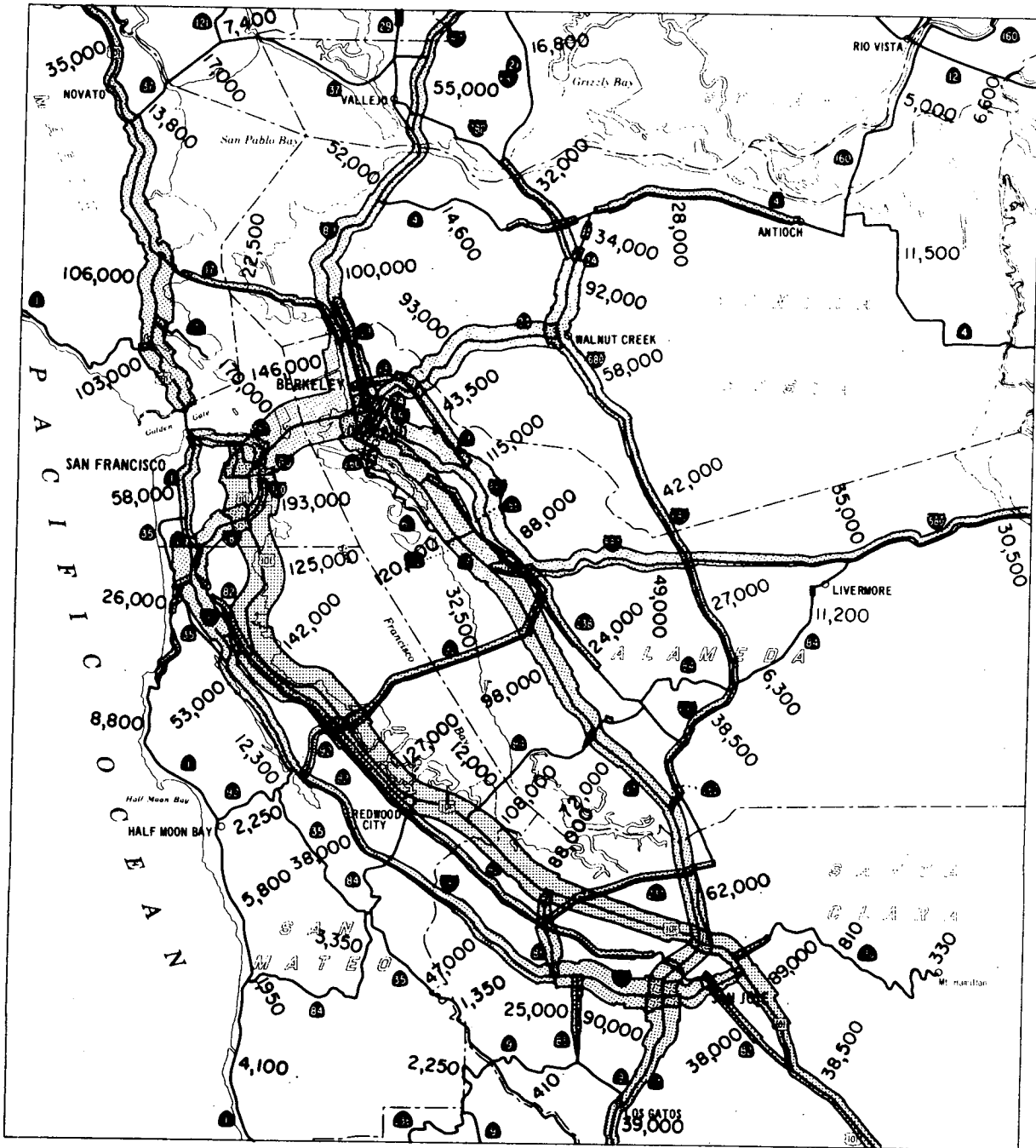


Fig. 2.7. Ratio of yearly travel to 1957 travel on California Freeways and roads (Source: California Department of Transportation).

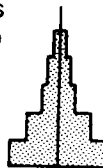
density intrastate arterials included in the state highway system.

Figure 2.9 is a similar map for the San Francisco Bay Area. A basic roadway power network in the area was estimated to require 219 freeway miles (438 lane miles) of system (352/705 km). This network would allow electric vehicles to travel anywhere in the metropolitan area and well into surrounding rural areas. A key factor is that for each mile of power system, 20 or 30 adjacent square miles can be served by electric vehicles.

It will be shown that the system is cost effective on a road with moderate-to-high average daily traffic, whether two lane or freeway. To achieve maximum utility, however, vehicles should have access to a network of surrounding powered roadways. In early phases to implementation this will be most feasible in larger metropolitan areas.



20,000 OR LESS
 40,000
 75,000
 100,000
 200,000
 300,000



1974
AVERAGE DAILY TRAFFIC
 IN THE
SAN FRANCISCO
AND VICINITY

SCALE 1 INCH EQUALS APPROXIMATELY 5 MILES

Fig. 2.9. Average daily traffic in San Francisco and vicinity, 1974.
 (Source: California Department of Transportation.)
 (XBL 769-10660)

3. Design Considerations

3.1. DESIGN REQUIREMENTS FOR THE SYSTEM

3.1.1. Power Coupling Capacity

The maximum traffic capacity of a roadway lane without automatic controls is approximately 2000 vehicles per hour. This capacity is reached with vehicles operating at 40 miles per hour and spaced at 50 vehicles per mile. The relationship between lane capacity and speed is shown in Fig. 3.1. The discontinuity that occurs at 40 miles per hour is said to result because orderly traffic flow is easily upset above that speed by minor accelerations, decelerations, or other small perturbations.

The DMET vehicles will carry batteries or other stored energy systems of a size to suit the off-system range requirements of a particular user. The charging power required for lead-acid battery packs up to 800 pounds would approximate 4 kW. The maximum system power load vs traffic speed was derived from the vehicle loadings shown in Fig. 3.2, and a vehicle power load equal to its propulsion requirement plus a 4 kW charging allowance.

3.1.2. Compatibility with the Roadway Environment

3.1.2.1. Surface Irregularities. It is advantageous to design the roadway power coupling for physical clearances of the order of 1 in. Extra clearance requirements result in designs with increased costs and more stray magnetic field near the power source.

Some data regarding surface irregularities in typical roadways have been obtained. Part of the data come from the California Department of Transportation (Caltrans); part from a test made as part of this investigation.

California freeways are continuously monitored as to surface condition. Roads that exceed roughness tolerances are reconstructed or resurfaced. Figure 3.3 is a photograph of a "bridge profilograph" and a typical graph from a freeway lane, showing measured surface irregularities.

In the graph, each vertical division represents 0.1 in.; each horizontal division represents 25 ft. The periodic major perturbations

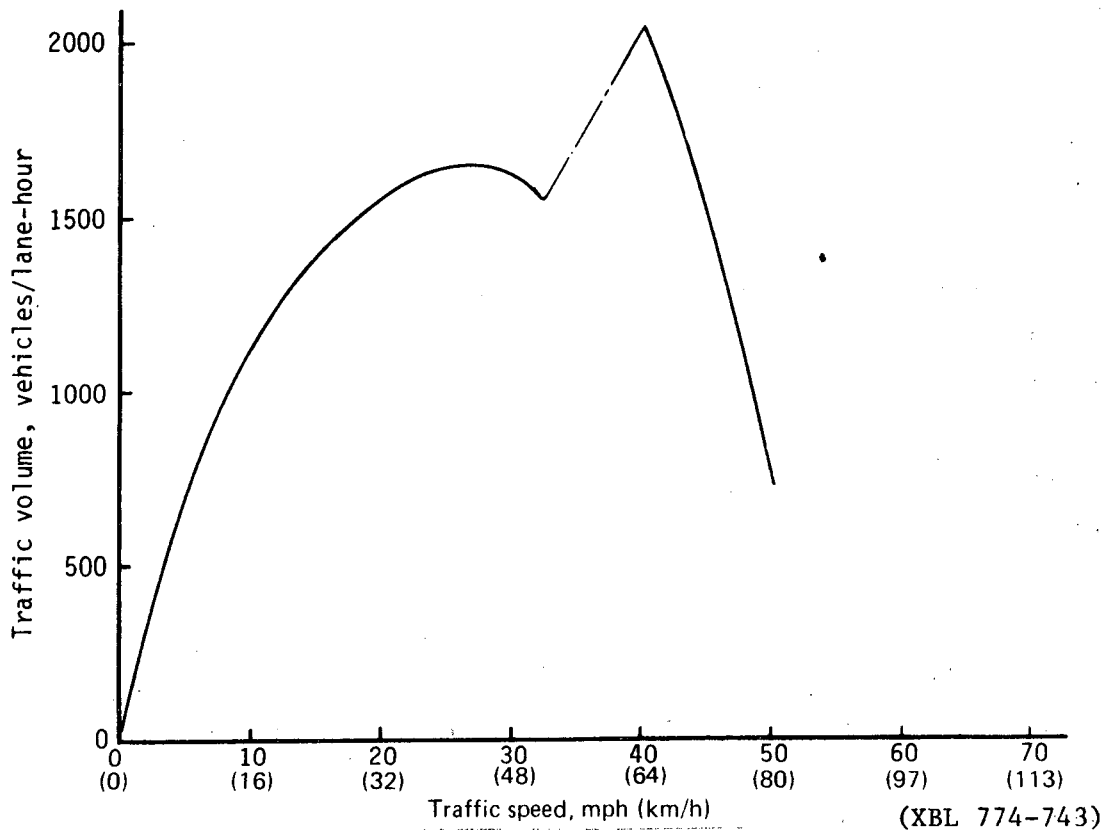


Fig. 3.1. Highway traffic volume vs speed. (Source: Drake, Schofer, and May, "Eddie Hypothesis," Highw. Res. Rec. 154 (1967).

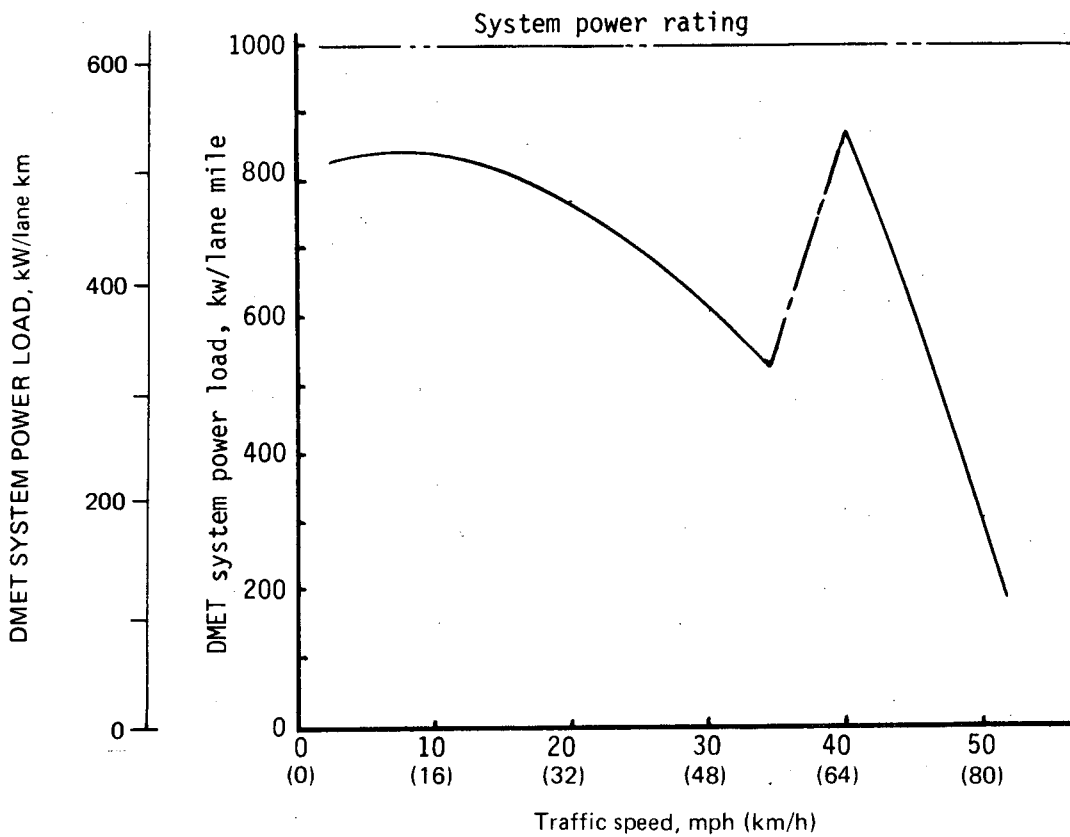
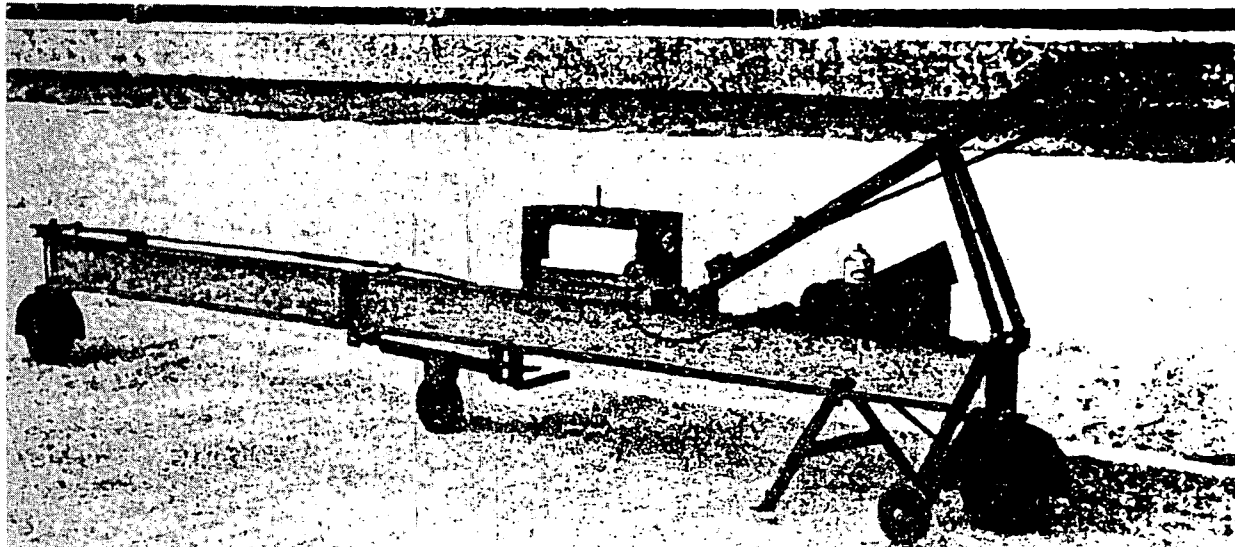
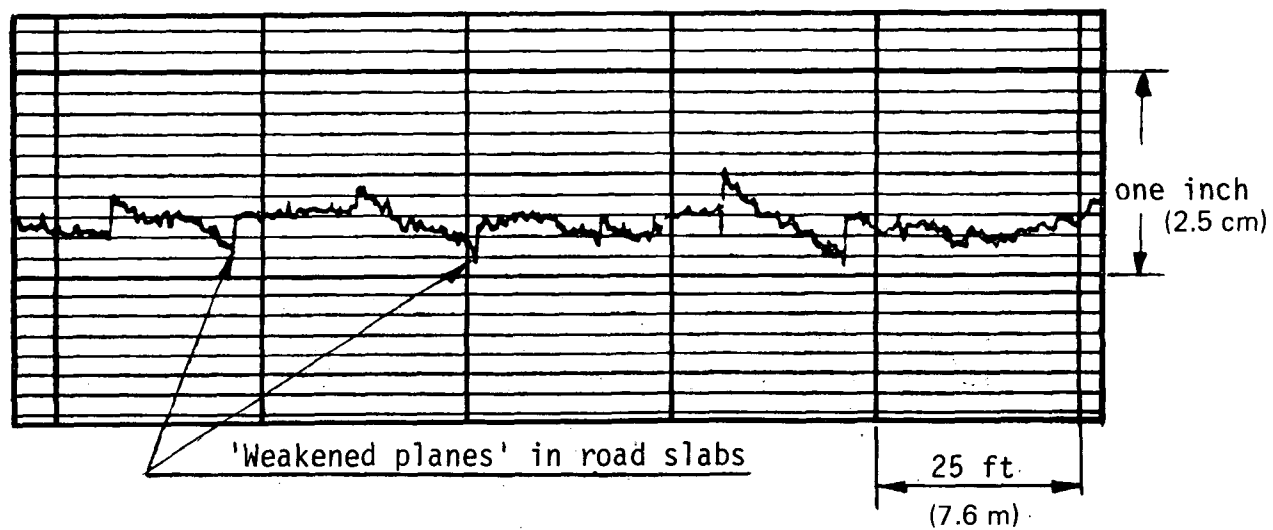


Fig. 3.2. DMET system power load vs traffic speed. (XBL 774-744)



BRIDGE PROFILOGRAPH



PROFILOGRAM

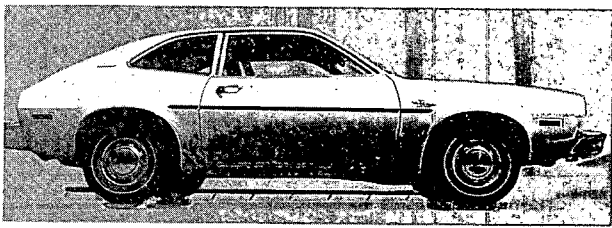
Fig. 3.3. Bridge profilograph and profilogram (Source: California Department of Transportation). (XBL 774-745)

on the graph are surface discontinuities at "weakened plane points," which are diagonally sawed cuts in roadways whose purpose is to control the location of the fractures that provide strain relief to roadway slabs. The graphs show that in a span typical of the wheelbase of an automobile (~8 ft) a maximum surface displacement less than 0.3 in. (0.8 cm) can be expected.

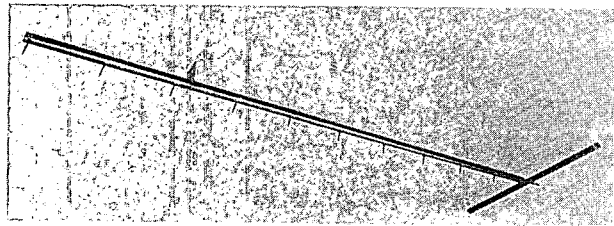
The "spring rate" of 13-in. radial tires is approximately 4000 pounds per inch (715 kg/cm) for four tires, which indicates that tire deflections are of little concern in maintaining acceptable air gap tolerances.

A practical clearance (airgap) should provide not only for normal road-surface variations, but also for tire deflections, unusual road surfaces, and pickup suspension characteristics. A preliminary assessment of these factors was made from tests made with a fixture suspended below a subcompact automobile. Figure 3.4 includes a photograph of the fixture. The fixture consists of a 10 ft-long 1-1/4 in.-diameter light-wall steel tube, which was suspended in the plane of the vehicle's centerline with approximately 2 in. of clearance above the roadway. The length of the tube extended from about 6 in. behind the front wheels to 2-1/2 ft behind the rear wheels. The fixture was suspended from the center of a transverse beam between the two front wheels; the rear support was from the differential housing. The elevation of the fixture was thus referenced to the average elevation of the front and rear wheel pairs. Attached to the fixture's bottom surface at 1-ft intervals were soft steel "feeler" wires, annealed to prevent "springback."

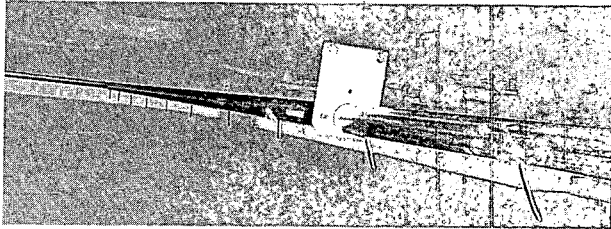
The test began on the shoulder of a freeway on-ramp, where the fixture was slipped into its supports while the vehicle was elevated with blocks under its tires. The vehicle was then driven for several miles on the outer lane of a freeway selected for unusual roughness. The vehicle was again driven onto blocks and the fixture removed for measurement of the projection of the feeler wires below the fixture. These projections were compared to the distance of the fixture to the reference plane of the wheel-road interface to determine how much they had been bent by freeway and road shoulder surfaces. From these data, it can be deduced that an airgap slightly more than an inch can be



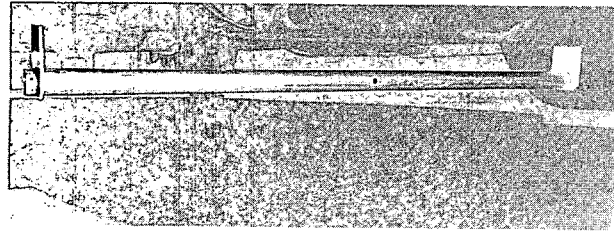
Vehicle with fixture



Fixture



Rear support (differential)



Front support crossmember

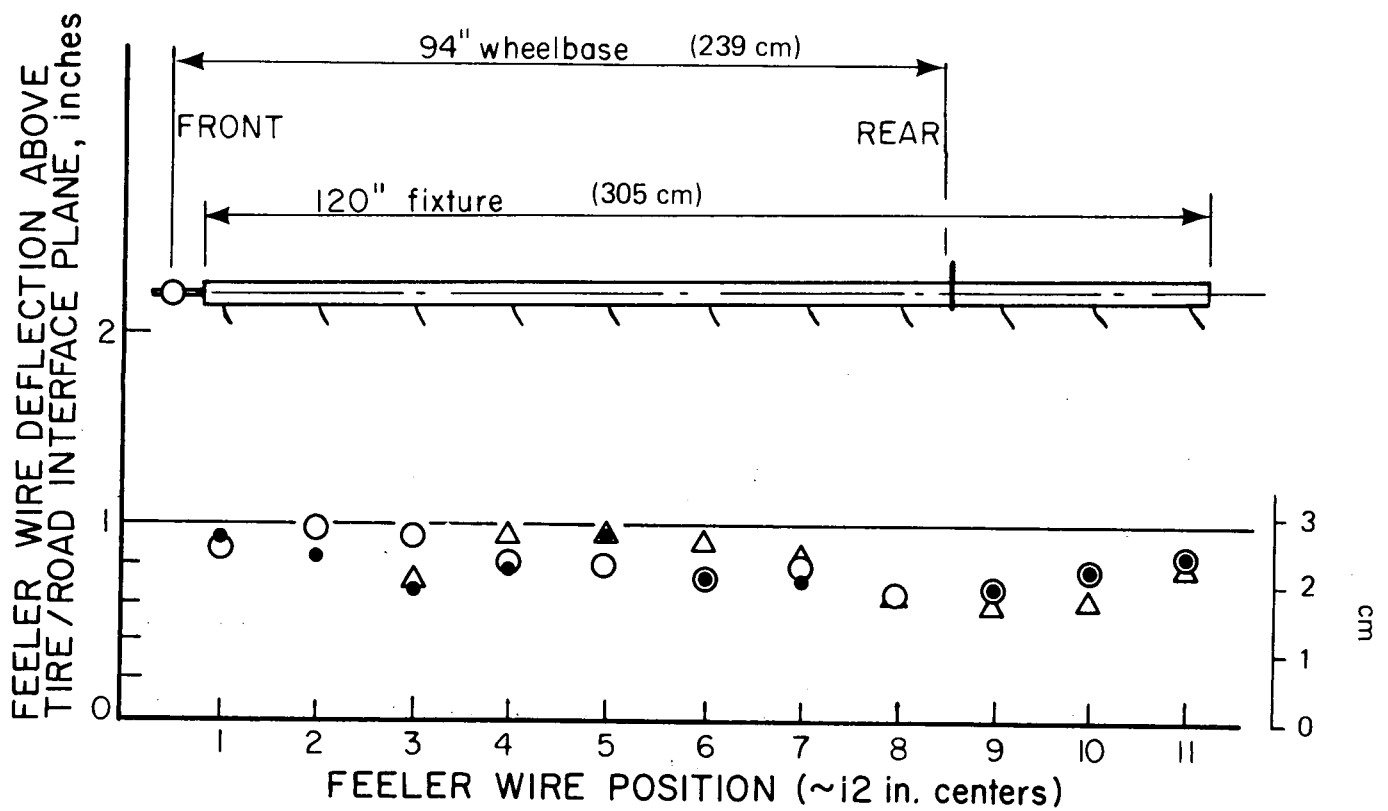


Fig. 3.4. Determination of clearance (airgap) requirement with a test fixture. (XBB 773-2619)

expected to provide adequate clearance, even on rough, patched roads and road shoulders. The data also indicate that pickup length has little relationship to the clearance required.

3.1.2.2. Mechanical Requirements for the Source. The surfaces that the source presents to the roadway must withstand the abuses typical of highways. Resistance to the abrasion of tires and impacts from falling objects are essential. The surfaces should also provide frictional properties that are similar to the adjacent roadway surface. Vehicles should not experience a discontinuity in steering characteristics as they drive over the source.

Preliminary investigations of options in source construction are currently exploring the use of a design as shown in Fig. 3.5. The "granular magnetic material" indicated in the figure could consist of a mixture of processed magnetite ore, which is over 70% iron, and ordinary cement. Such materials have been used to make shielding blocks for enclosing sources of nuclear radiation where high density is desired. In this application the magnetic permeability of the material is of advantage in transmitting magnetic flux, and the frictional properties of the concrete-like substance are similar to ordinary concrete roadways. Such surfaces can be expected to tolerate the grooving or grinding operations used to maintain concrete roads.

The center section of the source's roadway surface is conceived to be made of a fiber-reinforced insulating board. It may be necessary to have a special board developed in order to achieve good resistance to oils, chemicals, and impact, and have suitable frictional characteristics.

Roadways are subject to settling, cracking, and heaving. The source must tolerate such deflections without damage or malfunction. It is conceived that the source's steel core will be constructed in lengths of the order of from 3 to 6 ft (1 to 2 m) with gaps at each joint. The electrical conductor in the source could be made up of many strands of aluminum, sealed and protected by a tough elastomer. These techniques may provide the required tolerance for relative motions and thermal expansions and contractions.

The installation of the source should provide the ability to adjust the elevation of the source to accommodate resurfacing operations. Figure 3.5 illustrates a design option that provides a threaded height adjustment. Subsequent grouting under the source would be used to accomplish the transfer of road loads to the underlying slab.

3.1.2.3. Effects of Stray Magnetic Field. Magnetic flux emanating from the source core will circulate through the steel structure of conventional vehicles that occupy a powered lane. Figure 3.6 is a reproduction of a computer plot showing the magnetic flux that would be transmitted through a vehicle's sheet-metal floor pan. This plot shows that the passenger compartment of such a vehicle will contain a negligible amount of magnetic flux. The plot also indicates that flux would flow transversely through the sheet metal. The maximum power dissipated in the sheet metal would approximate 0.2 W/in.^2 in this example. With the vehicle at a standstill, the temperature rise in the sheet would approximate 11°C ; at 40 mph (64 km/h), typical average freeway speed, the temperature rise would be reduced to approximately 4°C . The thermal flux radiated from an exhaust pipe at 120°C is about 3 times this magnitude. Thus present automobile designs could be expected to accommodate the DMET thermal input without problems. Other thermal effects of the magnetic field are discussed in Section 3.1.3.

Figure 3.7 shows the intensity of the magnetic field from the source for a hypothetical roadway installation. At a height of 34 in. (86 cm) above the roadway the flux density reaches a maximum of 4 gauss at the centerline of the source and drops to 0.6 gauss at a distance of 6 ft (183 cm) from the source (i.e., at the edge of the lane). This alternating flux intensity is approximately equal to the (steady) intensity of the earth's magnetic field. The presence of an adjacent powered lane causes the flux intensity to be asymmetrical with respect to the lane centerline.

Three millivolts per foot (10 mV/m) would be induced in a conductor along the edge of the roadway with the circuit completed by a parallel return conductor at an infinite distance. While alternating voltages of this magnitude would be highly unlikely to cause large circulating currents in conducting structures, they would be troublesome if induced in instrument or communications circuits. Useful techniques in avoiding such problems are to increase the distances from those circuits to the source, or to utilize traps sharply tuned to source frequency to bypass induced voltages.

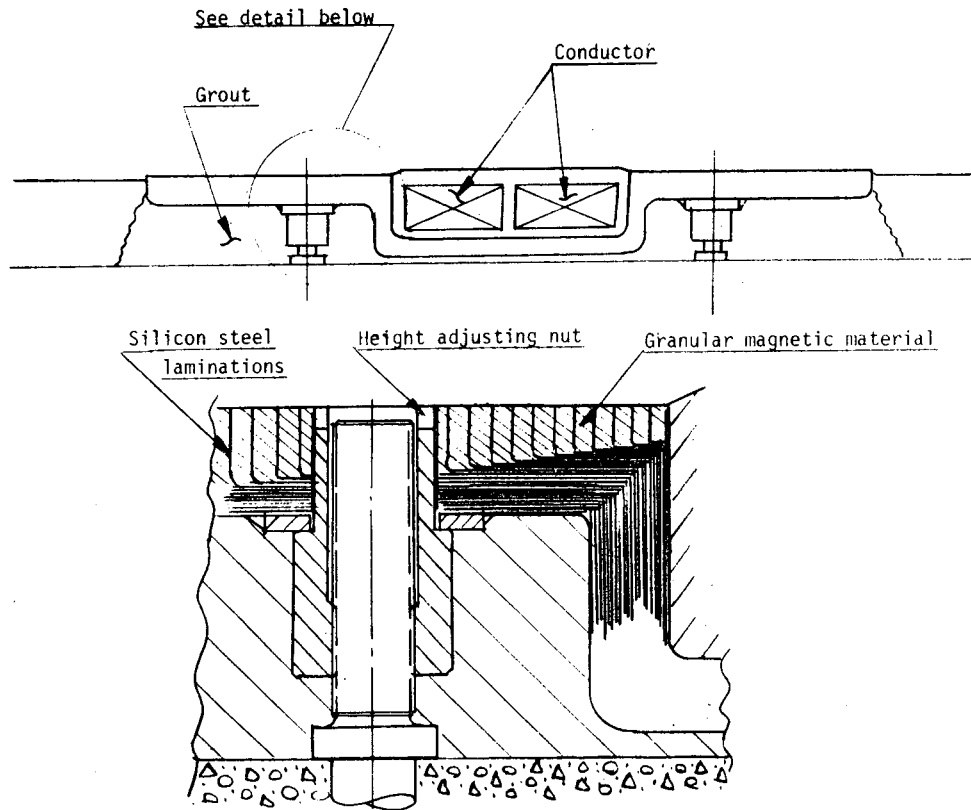


Fig. 3.5. Source installation concept. (XBL 774-746)

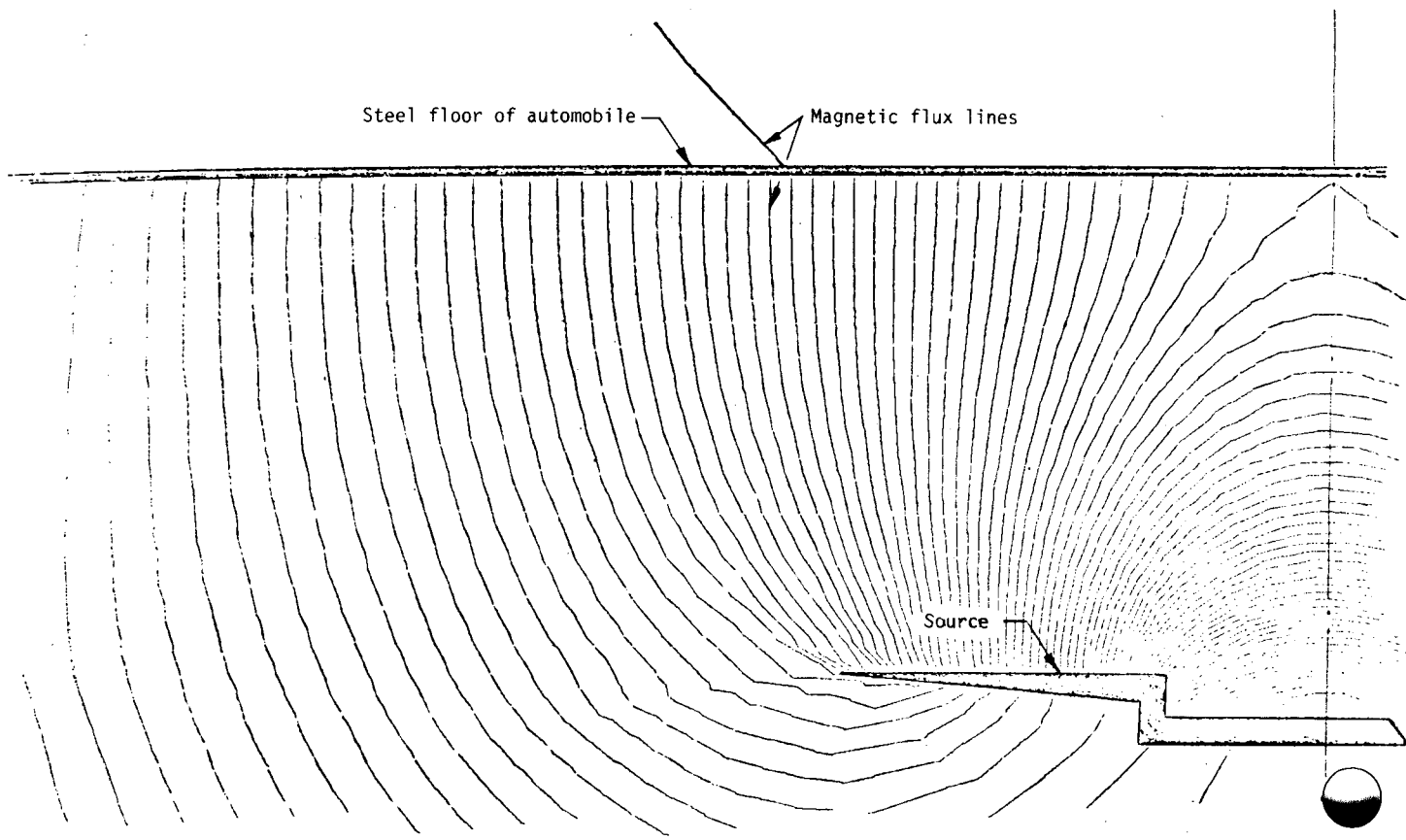


Fig. 3.6. Flux plot showing the effect of the presence of a conventional vehicle above the source. (XBL 774-747)

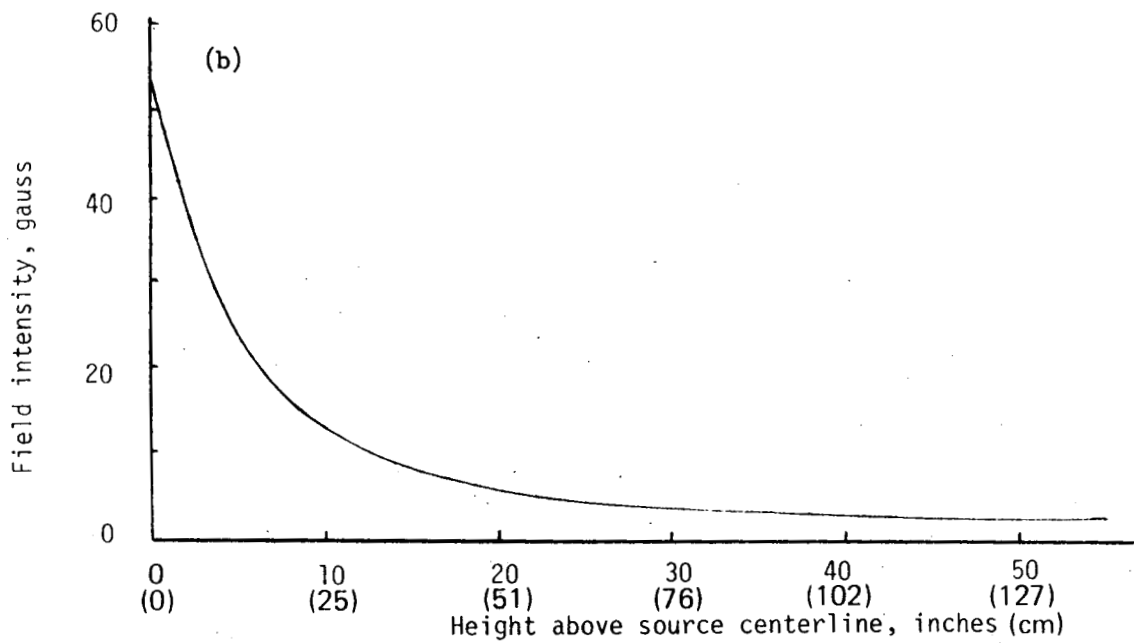
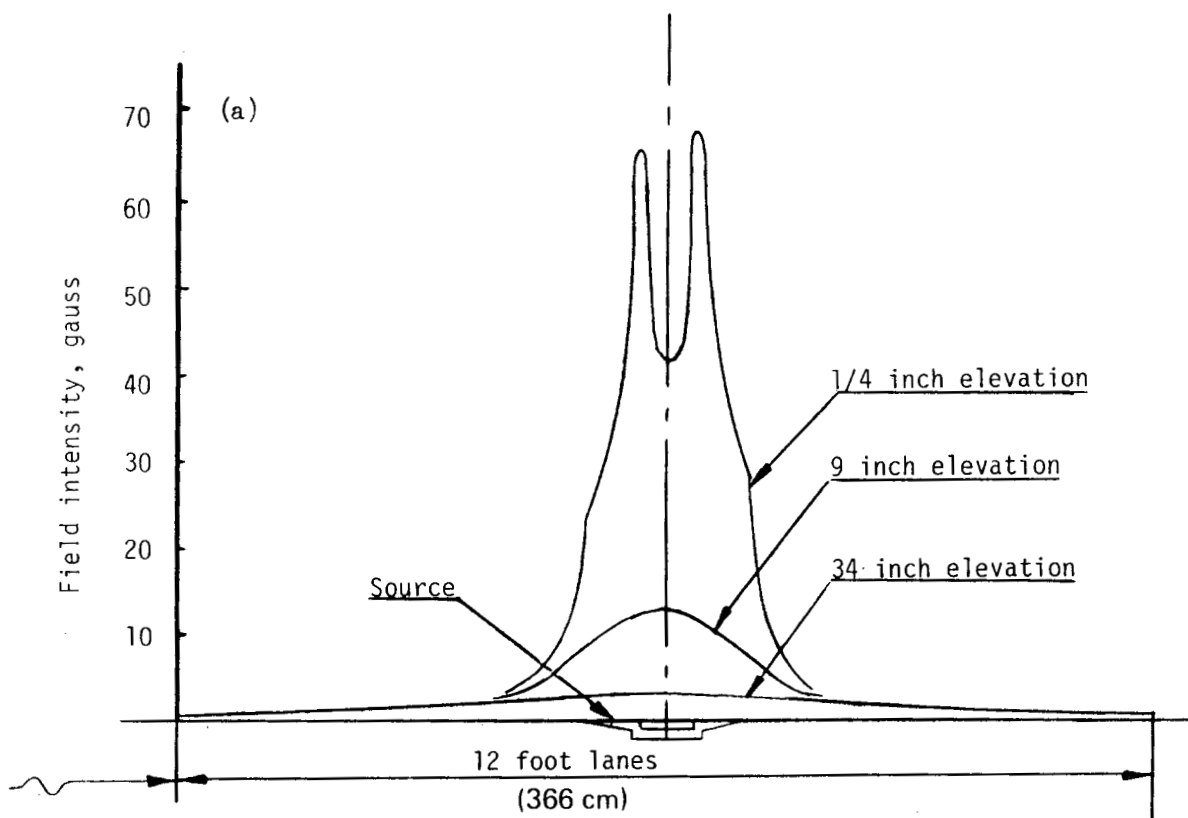


Fig. 3.7. (a) Field intensity vs distance from source; (b) field intensity vs height above source center. (XBL 774-748)

Problems relating to voltages induced by power transmission lines have been the subject of research for many years. The DMET development program should provide for a comprehensive review of such research to identify any problems that may occur and techniques that have been developed to solve them. Investigations of the effect of magnetic fields on humans have shown that the fields from the DMET system would have no physiological effect on people.⁴

3.1.3. Safety

3.1.3.1. Electrical. Several possible hazards have been recognized with regard to DMET power systems. One is the high voltage in the conductor in the roadway power source. This voltage may be from 2000 to 3000 V per mile (1240-1860 V/km) of powered circuit, isolated from ground. There is only a single conductor in the source, so that catastrophic short circuits will be highly unlikely. Although the penetration of the insulation above the conductor by metal objects would be very difficult, the possibility will exist. Capacitively coupled currents from ground to the penetrating member could be hazardous in such an occurrence. Effort should be devoted in the development program to determine the most effective means of detecting electrical faults in the power circuit for use in quickly interrupting the power to the circuit.

3.1.3.2. Magnetic. A second possible hazard is the effect on heart pacemakers of the stray magnetic field from the source. This hazard may not be significant, since the magnitude of the source current is similar to that which flows below the floor of rapid-transit cars and in welder's cables, which do not cause problems from the radiated magnetic field. The vulnerability of such devices should be more carefully assessed, however.

3.1.3.3. Roadway Debris. The magnetic field of the source can attract and hold ferrous materials. The clearance between the power source in the road and the power pickups suspended below vehicles is such that objects thicker than an inch will be struck by the pickups. It is unlikely that the steel structure of the pickup would be damaged, but the impacted object could become a hazardous projectile capable of smashing windows or damaging components of vehicles' running gear.

3.1.3.4. Thermal Effects. Magnetic flux will circulate through steel objects that overlies both poles of the source. Hysteresis and eddy-current losses will heat the objects to temperatures dependent on the amount of circulating flux and the geometry of the object. Figure 3.7 showed the intensity of the magnetic field near a roadway power source with 800 A (rms) of current. The figure illustrates the rapid fall off of field with distance from the source. The peculiar spikes in flux at an elevation of 1/4 in. above the source are due to the effect of field concentrations at the hypothesized sharp corners of the source's steel core. In actual construction such corners would be rounded and the field spikes would be moderated. These data were used to estimate the "worst case" heating of the rim of a motorcycle's or bicycle's wheel as it drove along the centerline of the source. The rim acts as a "shorted turn" of a transformer. The power dissipated in the rims is shown in Table 3.1. The maximum temperature rise with static vehicles is shown to be 100°C. While this is a magnitude of some concern, it would not cause a component failure or a fire. Continuing work should strive to minimize these effects, and driving regulations relating to the DMET system should recognize and deal with them.

3.1.4. Efficiency

The losses of significance in a DMET system are:

- Resistive losses in the source conductor and vehicle pickup.
- Hysteresis and eddy-current losses in the source, vehicle pickup cores, and nearby steel debris or structures.
- Power conditioner losses, primarily in transformers, capacitors, and thyristors.

The daily average traffic density on California urban freeways is approximately 11.5 vehicles per mile (7.1 vehicles per km). At that traffic density, only 1% of the length of the roadway power source is coupled to vehicles' pickups. In order to achieve a high average system efficiency, the loss per unit length of the uncoupled source must be very low.

Table 3.1. Power Dissipation in Aluminum Alloy Wheel

Wheel	Diameter in. (cm)	Position	Power Dissipation in Rim	Estimated Temperature Rise	
				Still air	10 mph
Bicycle	27 (69)	☐ Source	120 W	100°C	60°C
Motorcycle	18.5(47)	☐ Source	200 W	100°C	60°C
Motorcycle	18.5(47)	30 in. (76 cm) from ☐	43 W	35°C	10°C

Hysteresis and eddy-current losses are inherently very small since the flux density in the core is very low when a pickup is not present. Resistive losses in the source conductor on the other hand are uniform throughout the length of the source, whether coupled or not. Thus the most important technique in reducing system losses is the use of a source conductor of a large cross-sectional area (low resistance).

The cost of a kilowatt that is continuously dissipated for 20 years is more than \$5,000 at current energy prices. The cost of aluminum conductor with insulated strands is about 90¢ per pound ($\$1.98/\text{kg}$)⁵, and silicon steel sheets cost about 30¢ per pound ($\$.66/\text{kg}$)⁶. Figure 3.8 shows why it is economical to minimize the resistive losses by increasing the area of the conductor. In the example shown the minimum cost occurs at 130 A per in.² ($20\text{A}/\text{cm}^2$); industrial wiring typically carries current at many times that current density.

A similar technique, i.e., using thick core sections to reduce the flux density, provides the basis for minimizing hysteresis and eddy-current losses.

3.2. POWER CONDITIONER REQUIREMENTS

3.2.1. Electrical Characteristics

The power conditioner must supply the roadway source with a relatively constant current at a frequency higher than the standard 60 Hz. The choice of frequency will be influenced by the ease of conversion and other considerations as described in Section 4. Figure 4.4 shows how the characteristics of the electrical load vary with traffic load on the source. Because a high percentage of the source has no coupled load (99% of the source at average traffic loading), the system load is highly inductive. As roadway traffic increases, the reactive component of the system load decreases, since the increased coupled loads are capacitively compensated to a high power factor. In order to avoid putting too much reactive load on the utility lines, compensation must be included in the power conditioner; however, the variation is not big enough to require the compensation to track the load. The system voltage changes only slightly from no load to full load as a result of the large improvement in power factor that accompanies the increased load.

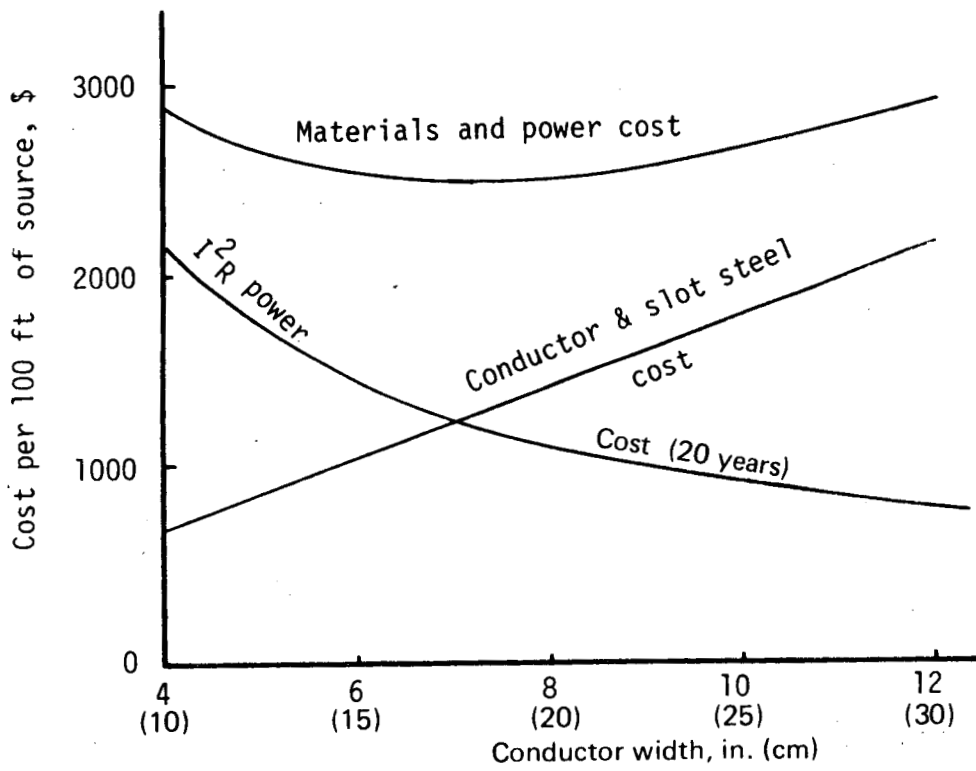
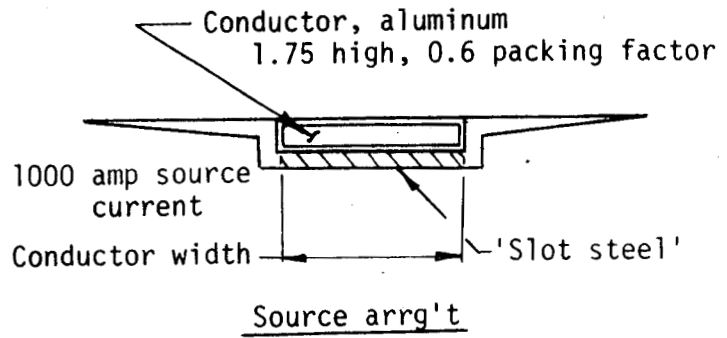


Fig. 3.8. Incremental cost vs conductor width. (XBL 774-749)

Close voltage and current regulation is not required of the power conditioner, because vehicles are capable of regulating the amount of power that they couple from the source. It is important, however, that the harmonic content of the load that the power conditioner presents to the utility is small. Harmonics are troublesome because of the increased eddy current and resistive losses and radiated interference that they cause.

3.2.2. Safety

As discussed elsewhere in this report, the power conditioner must include fault detection and a circuit interrupter that will turn off the power under any abnormal condition. Requirements for the device would be more stringent than for an industrial device since public safety is involved. Devices of this kind exist (e.g., differential relays for power systems and ground fault interrupters in hospitals, etc.). Further work will be required to find the most suitable device for the DMET application.

3.2.3. Control

Since the voltage does not change significantly with changes in loading, there is no need for a special controller. For safety reasons, remote shutoff controls at a central location may be necessary for DMET power networks.

3.3. VEHICLE REQUIREMENTS

3.3.1. Range

The DMET vehicle must have the capability of operating either from the limited supply of stored energy which it carries or from energy coupled from the roadway source. Existing electric vehicle technology offers a choice of power systems designed for battery-powered vehicles. The modified requirements of the DMET systems stem from the coupled power mode of operation, which supplies energy for freeway travel and recharging the stored energy.

The duty cycle of a typical metropolitan DMET vehicle will require only a limited range on city or suburban streets. The typical daily cycle of metropolitan vehicles consists of about 29 total miles (47 km)⁷, of which about 40% (12 miles) are on freeways and the remaining 60% (17 miles) are on streets.

Figure 7.6 shows that the maximum distance to the skeletal DMET network postulated for Los Angeles from any point in the urban area is less than 7 miles. Some perspective as to the effect on stored energy requirements of the limited street range is provided by the following example:

Required street range--2 × 7 miles =	14 miles (22 km)
Desired minimum state of charge =	40%
Energy required at 0.28 kWh/mile =	3.9 kWh
Battery weight at 13 Wh/lb = $\frac{3900 \text{ Wh}}{13 \frac{\text{Wh}}{\text{lb}} \times (1-0.4)} = 500 \text{ lb} \quad (227 \text{ kg})$	

3.3.2. Power Input

The battery pack of the DMET vehicle will be required to power the vehicle while it passes other vehicles on the freeway power lane, or changes powered lanes. A well-known phenomenon is the ability of the lead-acid battery to sustain very heavy loads for short periods with little degradation of the available stored energy. This phenomenon is of considerable benefit to the DMET vehicle in passing or lane-changing operations. A 500-pound battery could be expected to provide for such maneuvers by the vehicle characterized in this report.

The input power requirements of the characterized DMET vehicle are shown in Fig. 4.27. At 55 miles per hour (88 km/h) the requirement is 20.6 kW. At the present average freeway speed of about 40 miles per hour (65 km/h), 8 kW is available for battery charging without exceeding the nominal 20 kW rating of the DMET power coupling.

A characteristic of the DMET roadway power system is its ability to provide more than its nominal power rating; the penalty of overloading is a decrease in efficiency during the overload. This characteristic, in conjunction with the availability of stored energy, makes it possible to achieve high accelerations at highway speeds or to travel at higher than normal speeds with a DMET vehicle. Such capabilities, while not functionally essential, are probably requirements for a highly salable automobile.

3.3.3. Pickup Suspension and Power Regulation

The suspension of the power pickup of the DMET vehicle should maintain the clearance (air gap) between the pickup and roadway power source within tolerances of the order of 0.4 in. (1 cm). The electronic coupled power control on the DMET vehicles should be designed to accommodate variations in coupled power due to such airgap changes, and the stored energy pack will also aid in leveling variations in coupled power.

The suspension should also protect the vehicle and the pickup against damage in the event of a tire blowout, or an impact against an object on the roadway.

The pickup suspension must also raise the pickup to a height that provides normal ramp clearance while the vehicle operates on city streets.

3.3.4. Power Control

The power control unit on the vehicle has three functions:

1. Compensate for variations in power coupling characteristics. The characteristics will vary continuously because of airgap changes due to the quality of the road surface and because of misalignments caused by imperfect vehicle guidance.

2. Control the power to or from the motor as requested by the driver or an automatic vehicle control system. The power control must use power from the coupling and/or from the battery pack for propulsion. During braking cycles, regenerated motor power must be diverted to the battery or dissipated in resistors.

3. Regulate the rate of charge of the battery from the power coupling. The rate must be limited to the level that the battery will accept without damage and that the coupling can provide with good efficiency.

Preliminary computer studies have shown that the power that can be extracted from the coupling depends in part on the amount of compensating capacitance in the circuit. For each value of self- and mutual-inductance combination in the coupling magnetic circuit, there is an optimum value of capacitance for maximum power output. Since the self and mutual inductance change with coupling airgap and misalignment,

as shown in Fig. 4.5, automatic compensation is required to maintain a constant level of coupled power.

The use of a microprocessor to switch appropriate capacitors into and out of the circuit and to control other vehicle power circuits appears to be a feasible option for the power control.

3.3.5. Guidance on the DMET System

Guidance requirements for cars receiving roadway power will depend on the design of the vehicles' pickup and the pickup suspension. Investigations reported elsewhere in this report and Fig. 4.21 show a decrease in power coupling capacity as the pickup is offset from the source. Although the energy pack will support a vehicle's needs if it wanders beyond the point at which the coupling can supply the needed power, it is desirable to maintain a time-averaged coupling capability close to the maximum.

It is possible to construct pickup suspensions that automatically center the pickup over the source, or an automatic tracking servo can be added to power steering on the vehicle.

If these methods are not used, the driver will be required to steer the vehicle within a bandwidth approaching a foot. Figure 3.9 illustrates the results of measurements of the position of vehicles driven by typical motorists where the lane separation markers were the principal positional reference. The average offset from lane centerline is shown to be 0.56 feet (17 cm). It is likely that much more accurate guidance will occur naturally with the power system. The left edge of the source structure will provide a precise guidance reference directly in front of the driver; existing lane markers provide only an oblique position reference, which few drivers can use with any precision.

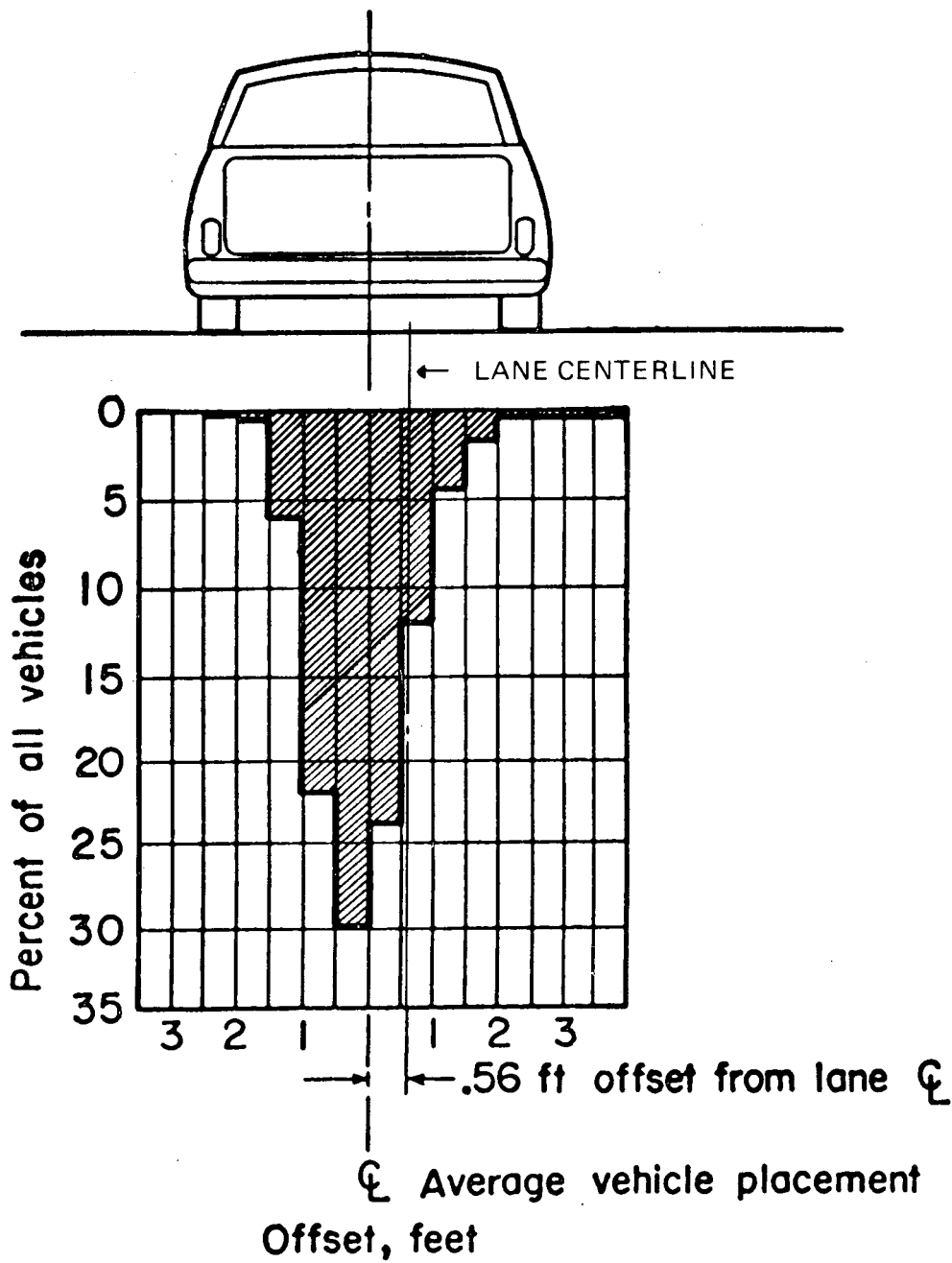


Fig. 3.9. Vehicle placement histogram. (Source: Highw. Res. Bull. 235 (1968); Texas Transportation Institute, Texas A&M.) (XBL 774-750)



4. Design Study

This section deals with specific technical investigations and analyses that were made during the course of the work. A fundamental tool used to illuminate areas of technical concern was the assumption of a system of arbitrarily chosen specifications. Although the assumed system necessarily was unoptimized, its use as a design study was a basis for exploring the analytic and rational processes that will be required for the design of actual systems.

The performance predicted for the design study system represents an approximate lower bound of what could be expected from actual systems. The project work has illuminated numerous potentially fruitful areas for the optimization of design parameters; these are dealt with in Section 4.1.

4.1. PARAMETRIC RELATIONSHIPS

The detailed design of a system such as this entails the careful study and evaluation of a large number of design tradeoffs. In making the preliminary study described in this report, estimates of reasonable values of various parameters were based on engineering judgment. As shown by the results of the study, these values resulted in a system that appears to be quite practical in terms of feasibility, cost, and complexity. As the study progresses, these parameters will be re-examined. In particular, the effects on the system of optimizing each parameter will be evaluated.

4.1.1. Electromagnetic Relationships

In an electromagnetic circuit such as the power coupling for this system, the relationship of induced (pickup) voltage to other circuit parameters is:

$$E \text{ is proportional to } \frac{f \cdot NI_e}{R}$$

where E = induced voltage

f = frequency

NI_e = exciting ampere turns

R = reluctance of magnetic circuit

4.1.2. Frequency

The optimum frequency will represent a tradeoff between several phenomena:

<u>Effect of Increased Frequency</u>		<u>Related Phenomena</u>
Size or weight	decrease	% of leakage flux increases (air gap = constant)
Core losses	increase	Can be compensated for by reducing flux density
Conductor eddy-current losses	increase	Can be compensated for by reducing strand size
Power supply	complex	Component size, cost, harmonic content in output
Coupled Interference	increase	Can be compensated for by reducing source current

4.1.3. Exciting Ampere-Turns

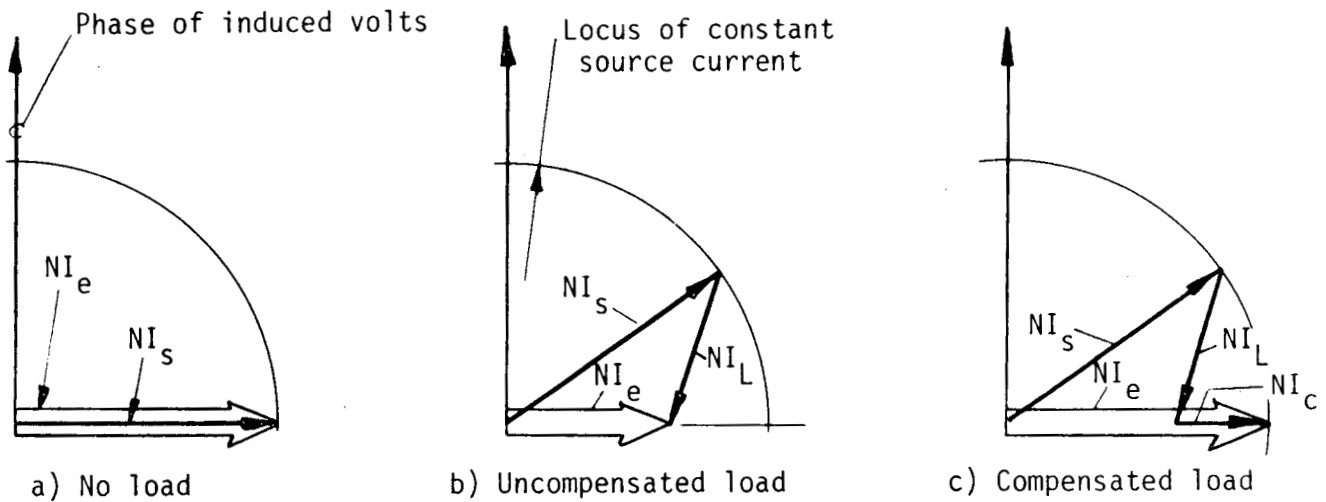
A vector diagram illustrating the relationships among exciting ampere turns NI_e , source ampere turns NI_s , and load (pickup) ampere turns NI_L is shown in Fig. 4.1. Figure 4.1(a) represents the coupled condition when the vehicle's electrical load is entirely disconnected. In this case, $NI_s = NI_e$ -- the source ampere turns are the only exciting ampere turns in the power coupling. In Fig. 4.1(b), an uncompensated vehicle load is applied. Uncompensated means that no capacitors have been added to the circuit to compensate for the partially inductive nature of the vehicle load. Note that, because of the vector relationship, the exciting ampere turns have diminished. Thus, the voltage (back emf) available to absorb power from the source current is, therefore, also diminished. Figure 4.1(c) shows the result of adding capacitive compensation, namely that NI_e has increased over Fig. 4.1(b) and again approaches the no-load conditions in Fig. 4.1(a). It is, in fact, feasible to adjust the value of C such that NI_e is larger than its no-load value.

NI_e = Exciting ampere turns

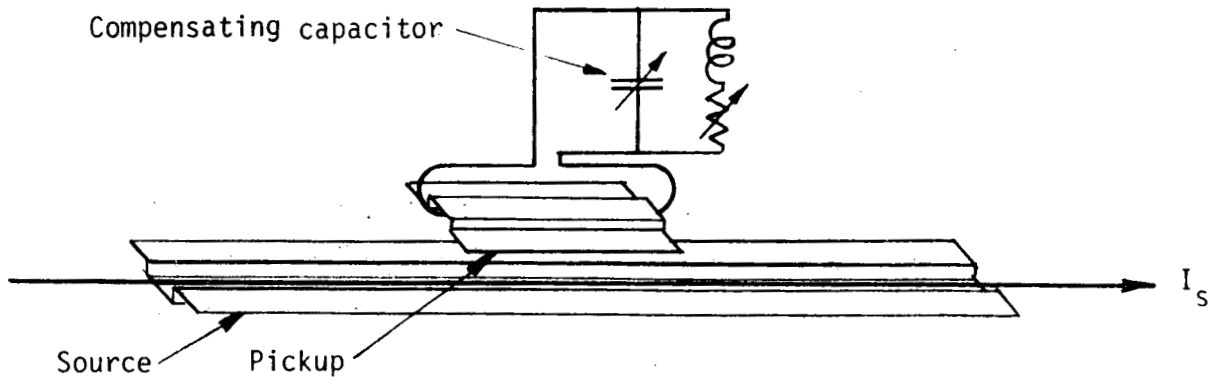
NI_s = Source ampere turns

NI_L = Load ampere turns

NI_c = Capacitive ampere turns



Coupling Magnetomotive Force Relationships



Coupling Schematic

Fig. 4.1. Coupling magnetomotive force relationships and coupling schematic. (XBL 774-751)

There are major advantages to utilizing a low source ampere turns NI_s . Among these are:

1. Reduced stray field and induced electrical interference.
2. Improved system power factor.
3. Reduced construction cost.

A problem that occurs with excessive use of capacitive compensation is the increased magnetomotive force $NI_L + NI_C$ to which the lower portion of the vehicle's body is exposed. The "return" conductors of the pickup winding contain ampere turns whose magnetic circuit path is above the pickup (see Fig. 4.2). The lower portion of the car's body should be carefully designed to avoid troublesome eddy current and hysteresis losses in metal parts. The difficulty of this design task will increase as the amount of ampere turns due to capacitive compensation increases.

4.1.4. Reluctance

The ampere turns required to induce a given voltage in an electromagnetic circuit is inversely proportional to its reluctance. It is important, however, to maintain an appreciable reluctance in the circuit. If, for example, the reluctance were very low (e.g., by using a very small airgap), the practical limit of exciting ampere turns would be limited to that which would saturate the coupling's steel cores, hence would also be very low. The maximum real component of pickup load ampere turns could not exceed the source ampere turns (i.e., the no-load source current) and thus would also be very low. Hence, the power capability of the coupling could be maintained only by increasing the induced voltage by increasing the amount of circulating flux. The physical significance of this is that smaller conductors could be used for the low current, but more core cross-sectional area would be required, and the source voltage and insulation requirements would increase.

This relationship represents a major departure of the characteristics of the power coupling from a typical transformer. A transformer is a device with very low reluctance, requiring a small number of exciting ampere turns. Because a constant voltage is applied to (and induced in) its primary winding, the circulating flux is constant; thus, changing

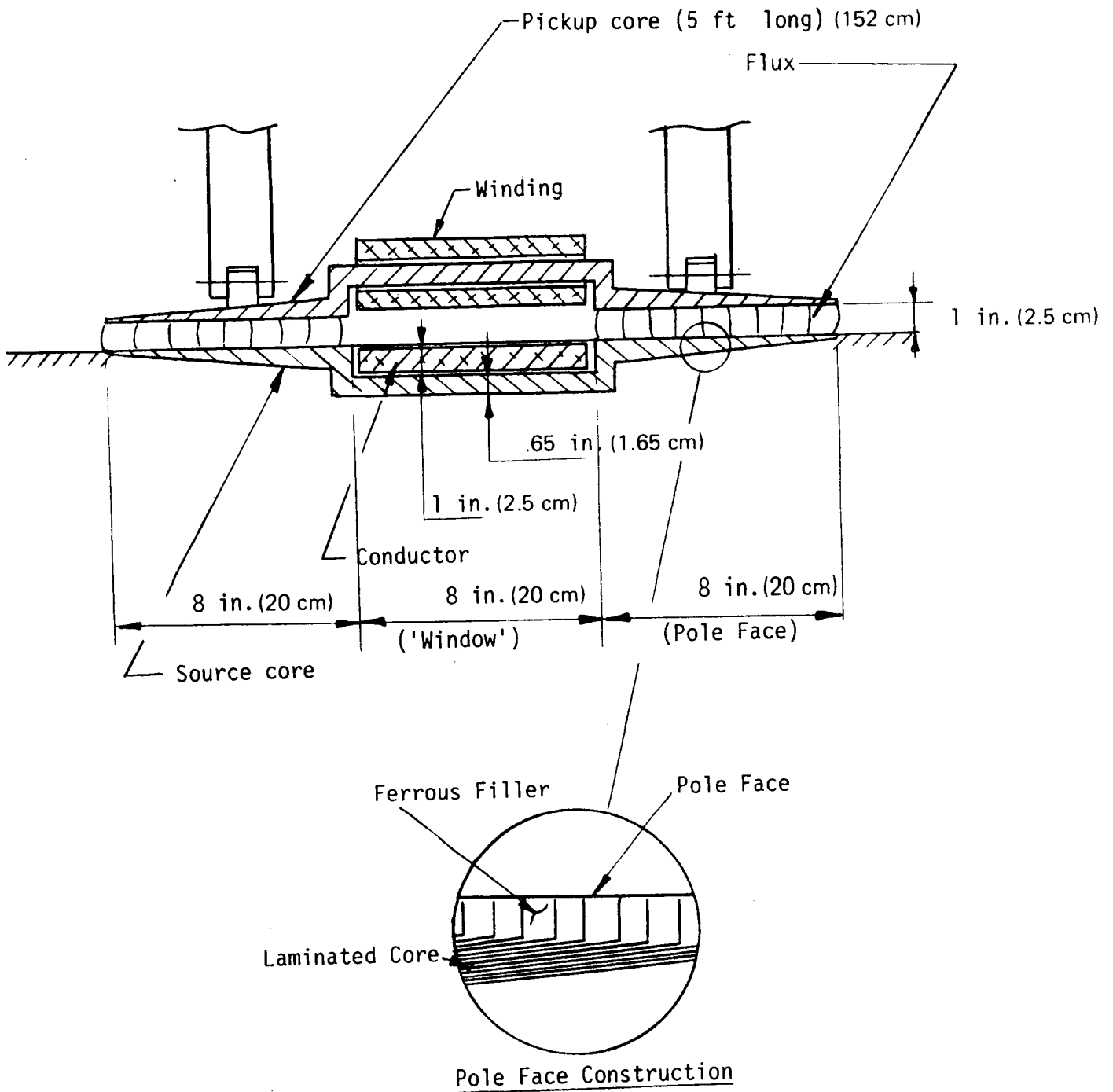


Fig. 4.2. Case study coupling cross section (8×8×8 in. source). (XBL 774-752)

load current (ampere turns) must be opposed by corresponding changes in primary current (ampere turns).

A constant source ("primary") current is used in this coupling. The current is high, but it does not saturate the magnetic circuit because of the reluctance introduced by the airgaps. Changing load would normally cause changes in the circulating flux were it not compensated by utilizing capacitive ampere turns as was shown in Fig. 4.1. Since the source operates with constant current and with roughly constant voltage, it is obvious that load variations result in corresponding phase changes.

The reluctance of the coupling resides predominantly in the airgaps. The reluctance is thus approximately equal to

$$\frac{2 \times \text{airgap clearance}}{\text{pole area}}$$

Practical ways to avoid excessively high reluctance in spite of large airgaps, while minimizing core materials and cost are to:

1. Use long pickups. An increase of pole area and reduced reluctance results, which allows less source current to be used. Since the maximum coupled power is a function of I^2 (power = $EI = K(NI) \times I$), the reduction in current will be related to the square root of the reluctance. Note that the weight of the pickup core does not change appreciably as a result, since the same total flux is circulated by a longer but thinner pickup core with the same longitudinal cross-sectional area.

2. Use wider poles. Although an increase in source core weight results, the increase is less than proportional because the poles are roughly half of the total core cross-section. An additional beneficial effect is in increased tolerance for offsets of the pickup due to guidance errors (discussed in earlier sections).

Because most of the reluctance of the magnetic circuit is in the airgaps, the reluctance is relatively insensitive to the permeability of the core material.

4.1.5. Magnetic Forces

A secondary effect of increased pole area is a reduction of magnetic forces between the source and pickup. Although the total flux required does not change as pole area increases, increasing the pole area decreases flux density proportionally. Magnetic forces decrease with the square of flux density; thus total magnetic forces are inversely proportional to pole area. Vertical forces on the pickup should be kept below magnitudes that have a significant effect either on the load rating requirements of the vehicle's tires and suspension or its rolling resistance. The proportions of the design study resulted in vertical forces of 161 lb; optimal proportions may significantly reduce that force.

Displacement of the pickup from a centered position brings restoring magnetic forces into play. These forces are a small fraction of vertical forces (a maximum of approximately 40 pounds with the case-study configuration) and thus will not be large enough to affect the vehicle's handling.

4.1.6. Losses

The loss processes in the roadway system are resistive losses and eddy-current losses in the conductors, and hysteresis and eddy-current losses in cores. Note that no power is lost in airgaps. Some losses also will occur in the structure of ICE vehicles that drive on the system.

Resistive losses are a function of conductor resistance, which is inversely related to conductor cross section. A large conductor cross section is used in order to reduce resistive losses in the source to less than 20 kW per mile (12 kW/km). Although this loss is of the order of only 1% of the full load rating of the source system, it is a continuous loss, unrelated to traffic load, and thus important to minimize. Eddy-current losses in the conductor are controlled by using insulated, stranded construction. The strands should be transposed in position periodically in order to equalize the voltages induced in each strand.

Hysteresis and eddy-current losses in cores are functions of flux density in the core, and construction details. The conventional means of reducing these losses in transformers involves the use of thin insulated sheets of silicon steel oriented parallel to the flux lines

(see Fig. 4.2) except for pole faces. Flux enters normal to the pole faces; one means of possibly achieving desirable pole-face configuration at low cost is indicated in the figure. The filler material indicated could be granular steel blended in size to obtain high-density packing.

The core losses are negligible when vehicle's pickups are not present. The losses in the coupled regions are held to low values by designing the core thickness to limit the flux density in the core to lower values than are typical in transformers. Losses at pole faces are minimal because the large pole faces that are used result in airgap flux densities of only a few hundred G when a pickup is present.

4.2. ROADWAY POWER COUPLING

4.2.1. Magnetic and Electrical Design of the Power Coupling Mechanism

The transfer of power from roadway to vehicle is accomplished by magnetic coupling. The coupling mechanism is somewhat similar to that in conventional power transformers; however, the physical design requires special comment.

The "primary" (called the source in this report) and one-half of the core of the "transformer" is imbedded in the roadway. It is a linear structure, with cross section as shown in Fig. 4.2. The core associated with the source includes two pole faces that are flush with the surface of the roadway. The "secondary" (called the pickup) is attached to the vehicle. The cross section of the pickup is similar to that of the source; when its two pole faces are above the two pole faces of the source, magnetic coupling results. Power can be efficiently transferred from source to pickup as in a conventional transformer. This occurs, of course, even though the vehicle's pickup is moving with respect to the roadway source.

The preliminary calculations presented here are intended to show the relationships among the basic parameters of the system and provide the bases for estimating the cost of the components and the operating efficiency of the concept. This design study uses arbitrary, unoptimized parameters, hence represents a probable lower bound of performance and an upper bound of cost.

4.2.2. Brief Description of the Power Coupling

The source winding consists of a single stranded aluminum conductor along the center of the traffic lane; the return leg to complete the electrical circuit is a similar conductor in an adjacent lane. The lane spacing is assumed to be 12 ft (366 cm). The conductor carries a current that is regulated to be approximately 1000 A at a frequency of 180 Hz.

A continuous iron core surrounds the lower half of the conductor. Its cross section is chosen to minimize its mass and yet keep the magnetic field low to reduce hysteresis losses. For the preliminary study, a cross section approximately 2 ft wide and 0.65 in. (61 cm × 1.65 cm) thick has been chosen (see Fig. 4.2). The center portion of the core is depressed 1 in. (2.5 cm) in order to accommodate the conductor. The edges of the core are tapered so as to retain approximately constant field intensity throughout the iron.

The vehicle's pickup is assumed to have a core of similar cross section, 5 ft (152 cm) long, separated from the roadway core by a 1 in. (2.5 cm) air gap. The windings for the pickup return along the top of the pickup core.

Based upon the power requirements for a typical small passenger car operating at highway speed, the vehicle is assumed to require a maximum of 20 kW through the magnetic coupling.

The thickness of the core (0.69 in.) is chosen to keep the peak field (when vehicle is present) to 10 kG. As described in Section 4.4, the simplified equivalent circuit of the vehicle contains an RC combination. The resistor R represents the vehicle power utilization. The capacitor C is used to compensate for the inductance of the coupling. In effect, it improves the power factor (at 180 Hz) of the power circuit of the vehicle. If capacitive compensation is complete (resonance), the current flowing in the pickup winding is more than twice that in the source. The field introduced by the pickup current is reduced by that due to the source current. The resultant field is equal to that produced by a current of 1000 A in either winding alone.

4.2.3. Analysis of the Source

The electrical and magnetic properties of the source depend on whether vehicle pickups are coupled to it, since the magnetic flux paths in the region of a pickup are strongly affected by its presence. In the following, we refer to a source without vehicles as the uncoupled source. It represents the idling condition of the electric roadway. When vehicles are present, and the magnetic flux lines couple both pickup and the part of the source under the pickup, it is called the coupled condition. Numbers are given in terms of per-foot of source length both coupled (under the pickup) and uncoupled.

4.2.4. Uncoupled Source

The inductance of the uncoupled source configuration was first estimated from manual flux plots. Subsequent computer calculations yielded very similar results. Figure 4.3(a) shows a computer-generated flux plot for the uncoupled condition.

In the absence of a vehicle (the uncoupled condition), the inductance of the core, the peak magnetic field, and the losses are relatively low, as shown in the left-hand column of Table 4.1. The eddy-current losses and hysteresis losses were determined from published data for transformer sheet steel with 29 gauge (0.014 in.) laminations, at the calculated magnetic field and chosen frequency. The conductor is comprised of many small strands in order to minimize eddy currents and their attendant losses. Zero eddy-current loss in the conductor is assumed in this preliminary analysis. The resistive losses in the conductor are for a total aluminum cross section of 4 in.², i.e., 50% packing within the coil slot.

As shown in Section 4.3 on power conditioning equipment, capacitors will probably be placed in series with the source loop to compensate for its 180 Hz reactance. The small losses for these capacitors are not considered in the analysis.

Table 4.1. Properties of the Source

General

Geometry: See Fig. 4.2
 Airgap: 1 in. (2.5 cm) Offset: 0 in.
 Frequency: 180 Hz Line current: 1000 A
 Power per car: 20 kW Power factor of source: 1 (corrected)

Core

Material: Transformer steel, 29 gauge (0.014 in.)
 Core thickness: 0.65 in. (1.65 cm)
 Unit weight: 37.5 lb/ft (56 kg/m)
 99.0 tons/mile

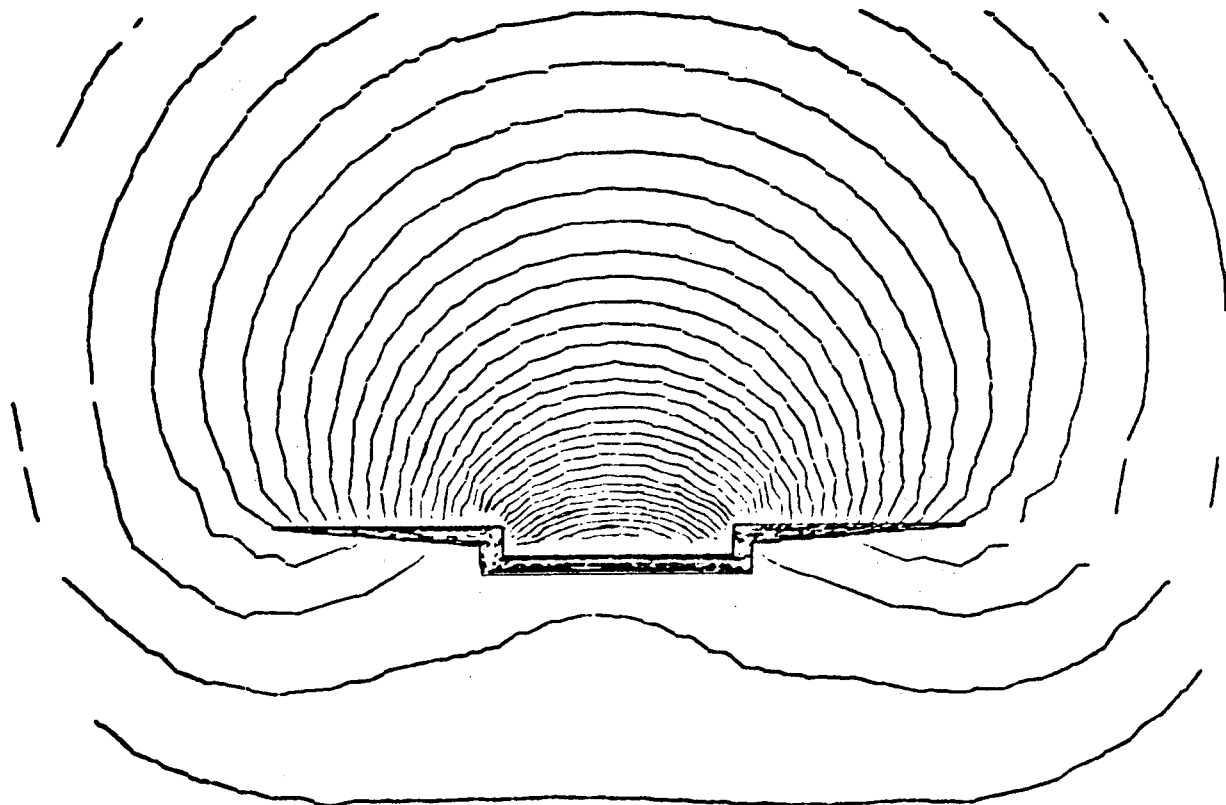
	<u>Uncoupled</u>	<u>Coupled</u>
Inductance: $\mu\text{H}/\text{ft}$ ($\mu\text{H}/\text{m}$)	0.387 (1.27)	1.83 (6.00)
Reactive V/ft (V/m)	0.437 (1.43)	0.0 (0.0)
Resistive V/ft (losses and load) (V/m)	0.0036(0.012)	4.189(13.74)
Maximum flux density in core: G, peak	544	10,000
Core loss: W/lb (W/kg)	0.0078(0.017)	1.55 (3.41)
Core loss: W/lb (W/m)	0.29 (1.0)	58.1 (191)
Uncoupled kVA/mile (kVA/km)	2307 (1434)	

Conductor

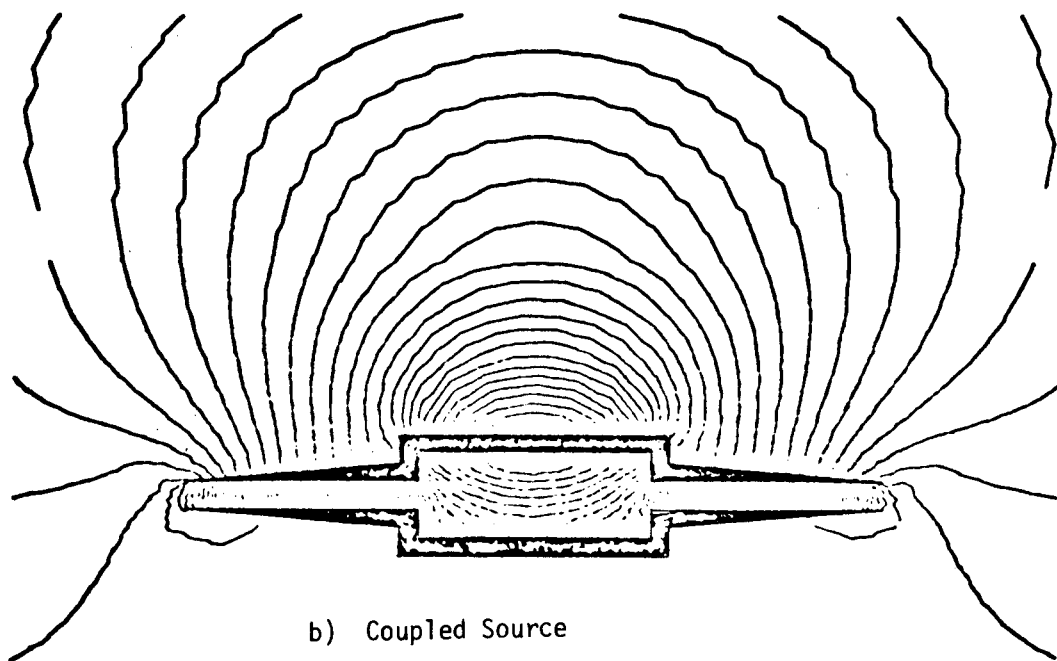
Material: Aluminum, stranded Resistivity: 2.8 $\mu\Omega\text{cm}$
 Winding slot dimensions: 1x8 in. (2.5 x 20 cm) Space factor: 0.5
 Conductor area: 4 in.² (25.8 cm²)
 Resistance: 3.31 $\mu\Omega/\text{ft}$ (10.9 $\mu\Omega/\text{m}$)
 Weight: 4.8 lb/ft (7.2 kg/m)
 12.67 tons/mile
 Resistive drop: 0.0031 V/ft (0.01 V/m)
 Conductor loss: 3.31 W/ft (10.9 W/m)

Costs

Core material cost: \$0.30/lb (\$0.66/kg)
 \$59,500/mile (\$37,000/km)
 Conductor material cost: \$0.90/lb (\$1.98/kg)
 \$22,800/mile (\$14,170/km)



a) Uncoupled Source



b) Coupled Source

Fig. 4.3. Magnetic flux plots of the source. (XBL 774-753)

4.2.5. Coupled Source

Figure 4.3(b) is a computer-generated flux plot for the coupled condition. The core in the pickup is assumed to be a mirror image of that in the source over the length of the pickup.

The right-hand column of Table 4.1 contains characteristics of the source when coupled to a pickup. These characteristics are affected by offset, i.e., the displacement between the center line of the pickup and that of the source. With perfect vehicle guidance, offset is zero. Later, the effects of offset are discussed. It is assumed that compensating capacitors are included in the vehicle so that there is no reactive current in the source for the coupled section.

4.2.6. Properties of the Pickup

Whereas the source has only a single conductor in the slot, the pickup will contain a full winding with the return leg lying on top of the core. The calculations have been normalized by assuming a single-turn pickup winding. In the final design, the number of turns would be chosen to provide an appropriate voltage to the vehicle's motor or energy storage pack.

A pickup length of 5 ft (152 cm) is assumed. This would be suitable for a passenger car. Other lengths would be used for other types of vehicles with other power requirements. End effects are ignored. The air gap between source and pickup is taken to be 1 in. (2.5 cm).

The vehicle load consists of the battery under charge, the motor and its controls, and capacitors for power control. For the analysis of the magnetic circuit, the leakage reactance in the source and pickup coil sections is assumed to be zero. Since the source current is 1000 A, a voltage drop (back emf) in the source of 4 V/ft will couple 20 kW into a unity power factor load, with the 5 ft-long pickup.

The loss mechanisms in the pickup are:

1. Hysteresis and eddy-current losses in the core.
2. Resistive losses in the conductor (which are increased as a consequence of the added reactive current of the capacitors).
3. Dissipation in the capacitors.

The total losses in the pickup are estimated to be 637 W or about 3% of the 20 kW useful load.

The total weight of the pickup, not including the suspension, is 235 lb.

Table 4.2 contains additional details.

4.2.7. System Efficiency Analysis

Table 4.3 is a summary of the efficiency and other pertinent characteristics of the system for various vehicle loadings. Figure 4.4 graphically shows these characteristics. It should be noted again that these figures are based on an assumption that all coupled vehicles are drawing a maximum design power of 20 kW from the system. In actual practice, the loads of individual vehicles will vary widely. In later analyses of system performance, this will be taken into account.

In the absence of any vehicle, the power consumption by the uncoupled source is 19 kW per mile which, of course, is all loss. Under this condition, the power factor is less than 1%. If the power factor were corrected to unity by series capacitors in the source circuit, the power consumption would rise to 26.7 kW due to capacitor losses.

As vehicles enter the roadway, the efficiency rises rapidly. For example, with only 5 cars per mile in a lane, the efficiency of the system without capacitor correction has already risen to 80%. The efficiency continues to rise with increasing vehicular load, reaching 95% at 100 cars per lane-mile. At this traffic density, the power factor in the absence of compensating capacitors is 0.7.

4.2.8. Notes on Computer Analysis of Power Coupling

The detailed flux distribution has been calculated for a number of geometries using a digital computer to solve the exact Poisson equation for iron of finite permeability but with the restriction that the problem is represented by its two-dimensional analog, and effects beyond 7 ft to either side are ignored. It is interesting to note that, even with the relatively large separation of the two halves of the magnetic circuit, flux coupling is nearly total. The leakage flux is mostly due to the source and pickup turns being in different locations in the magnetic circuit.

Table 4.3. Summary of System Efficiency Characteristics. Quantities are for One Lane-Mile of Source Loop.

Vehicles Coupled to System*	0	5	20	50	100
Coupled ft (m)	0	25 (7.6)	100 (30.5)	250 (76.2)	500 (152.4)
Uncoupled ft (m)	5280 (1609)	5255 (1602)	5180 (1579)	5030 (1534)	4780 (1457)
Coupled reactive V **	0	0	0	0	0
Uncoupled reactive V	2307	2296	2263	2198	2088
Total reactive V	2307	2296	2263	2198	2088
Coupled Resistive V	0	100	400	1000	2000
Total System V	2307	2299	2304	2442	2970
Source conductor loss, kW	17.5	17.5	17.5	17.5	17.5
Source coupled core loss, kW	0	1.5	5.8	14.5	29.1
Source uncoupled core loss, kW	1.5	1.5	1.5	1.4	1.4
Pickup power loss, kW total	0	3.2	12.7	31.9	63.7
Total system power loss, kW	19.0	23.7	37.5	65.3	111.7
Total reactive kVA	2307	2296	2263	2198	2088
Power factor of source circuit	0.008	0.054	0.190	0.441	0.730
Output power to vehicles, kW	0	100	400	1000	2000
Input power to source, kW	19.0	123.7	437.5	1065	2112
System efficiency, %	0	80.0	91.4	93.9	94.7

* Each car is assumed to be drawing full design load for passenger vehicles of 20 kW.

**When fully compensated with capacitors.

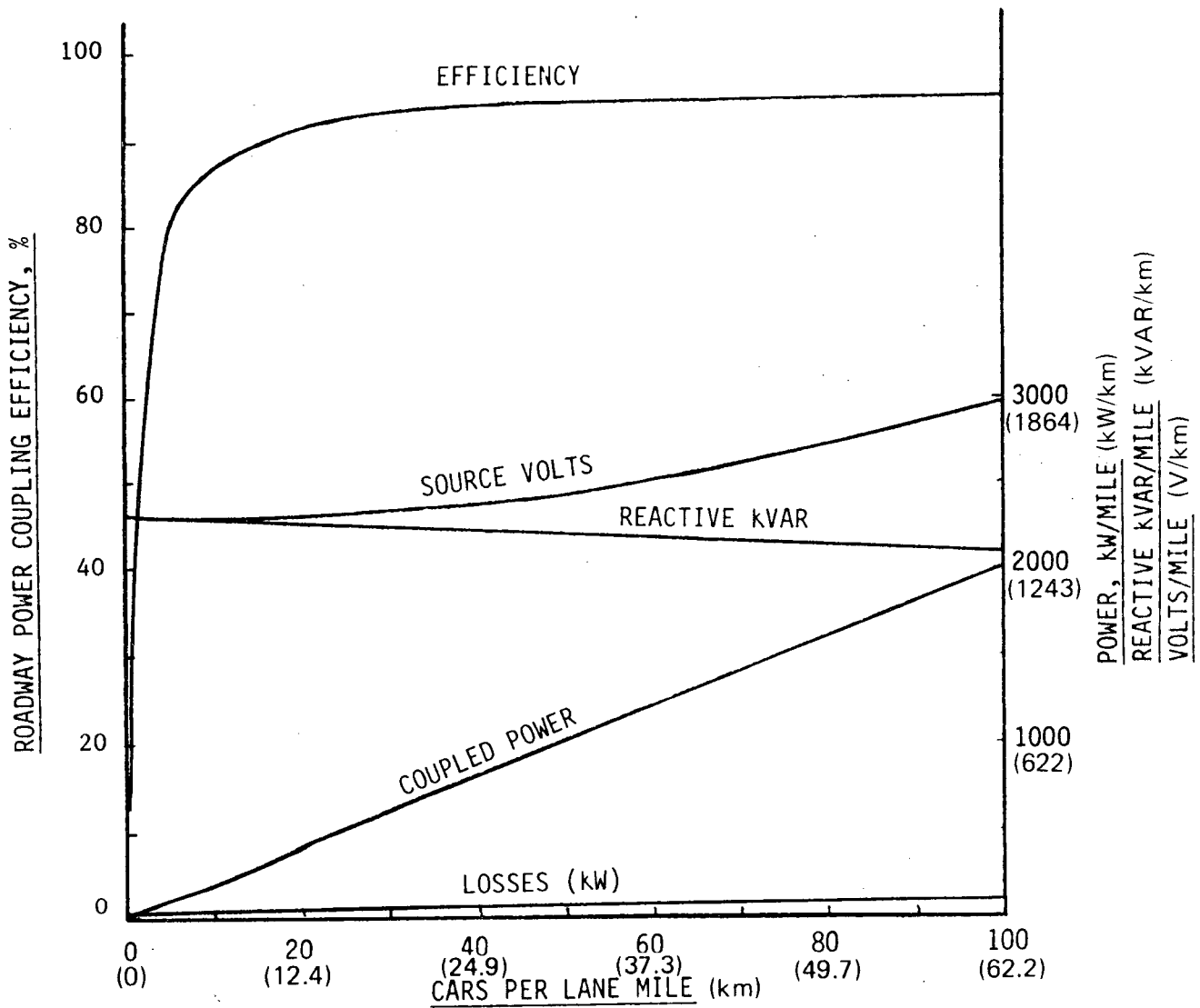


Fig. 4.4. Characteristics of roadway source with varying vehicle traffic load. Vehicle load is 20 kW/car (propulsion plus energy storage-pack charging). (XBL 774-754)

In addition to providing the magnetic flux plot, the computer code also calculates the total energy stored in the coupling. Since inductance, current, and energy are related, the three inductances (two self inductances and their mutual inductance) can be calculated by solving three cases with arbitrarily chosen currents.

It is shown that the coupling coefficient is 88.5% (i.e., the ratio of the mutual inductance to the geometric mean of the self inductances). In order to study the effects of vehicle lateral displacement and airgap variation, different geometric relationships were used. The air gap was increased to 1-1/2 in. (3.8 cm), and the pickup was displaced 2 and 4 in. (5 and 10 cm). The inductances for each case were calculated. These results serve as a basis for later calculations and are summarized in Table 4.4 and plotted in Fig. 4.5

4.3. POWER CONDITIONER

The roadway will need to be supplied with electrical power at a level that varies with the traffic density. At a maximum loading of 100 cars per lane mile (which can be attained with fully automatic vehicle control), the maximum power required is 2 MW per lane mile. For the purposes of this preliminary design study, it is assumed that this power would be supplied from the local electrical utility. Power conditioning stations would be situated at regular intervals along the roadway to receive power from the utility and supply it to the roadway source. Since the voltage and current levels and the frequency required by the roadway are not convenient to be supplied directly by the utility, the power conditioning stations would make the necessary conversions.

This section gives the results of the preliminary design study on the power conditioning stations. Cycloinverter and rectifier-inverter techniques for power conversion were examined. Both appear to be practical and economically feasible. The cycloinverter appears to have a net advantage, mainly because of its lower cost. The results of a study of a low-power model of the cycloinverter are given. In addition, a frequency tripler of the saturating core type is also possible, although information is not available for units of a size

Table 4.4.

		0 in.	2 in. (5 cm)	4 in. (10 cm)	0 in.
Lateral displacement					
Air gap	no car	1 in.	1 in.	1 in.	1-1/2 in.
	present	(2.5 cm)	(2.5 cm)	(2.5 cm)	(3.8 cm)
Source Inductance	$\mu\text{H/m}$	1.22	5.7	5.21	4.38
Pickup Inductance	$\mu\text{H/m}$	--	6.09	5.61	4.81
Mutual Inductance	$\mu\text{H/m}$	--	5.22	4.64	3.58

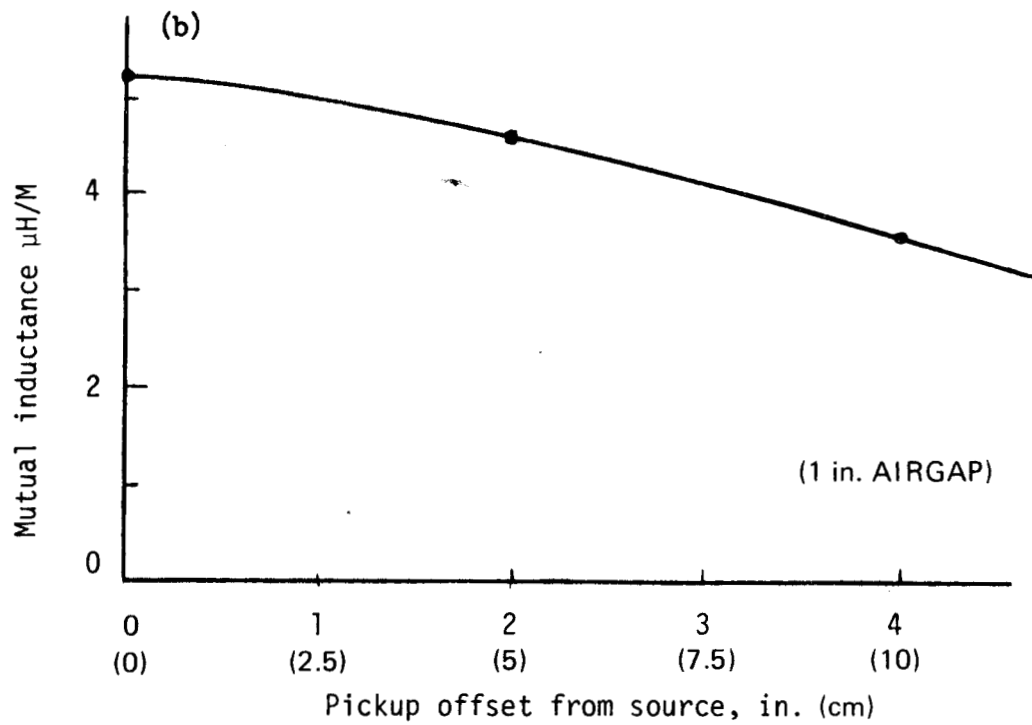
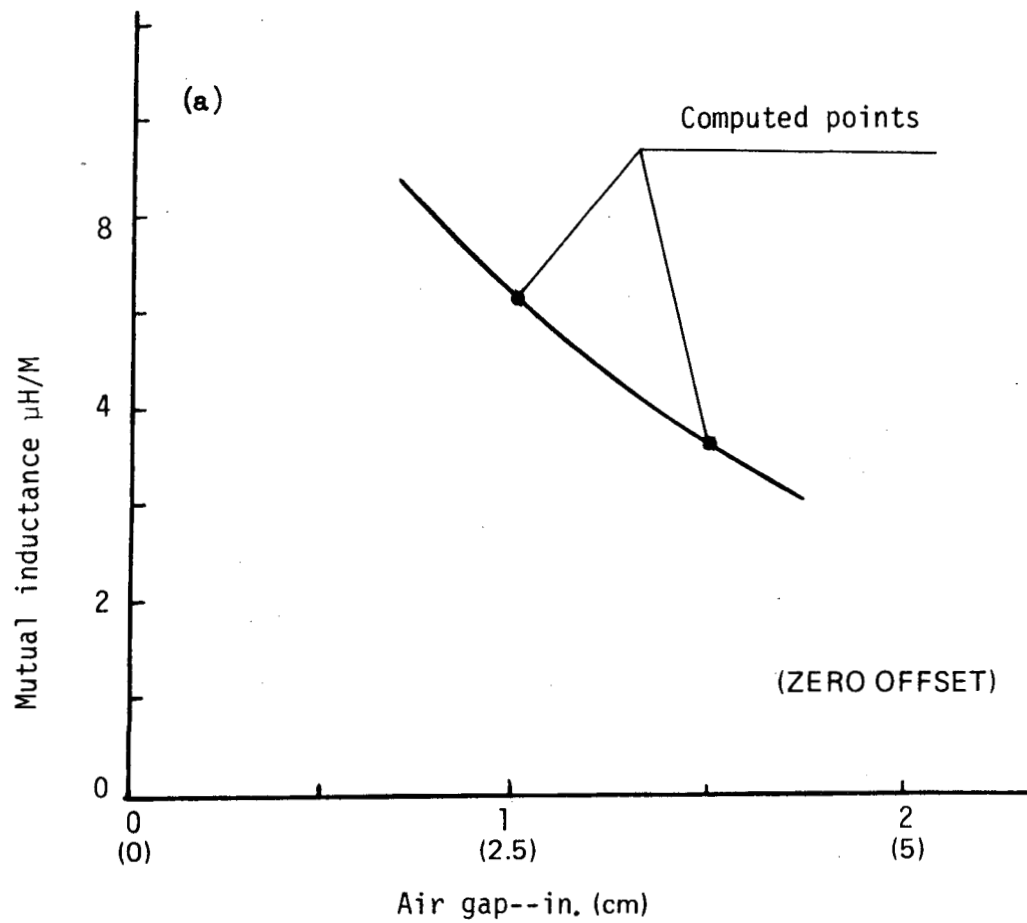


Fig. 4.5. (a) Mutual inductance vs air gap; (b) mutual inductance vs offset. (XBL 774-755)

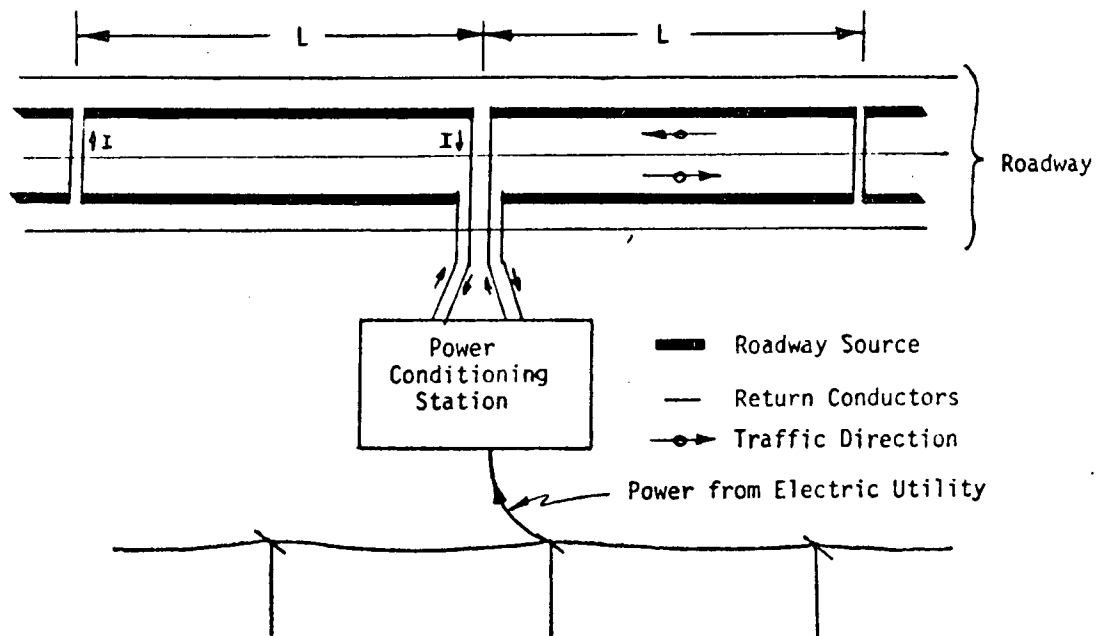


Fig. 4.6. Roadway power system schematic. (XBL 774-756)

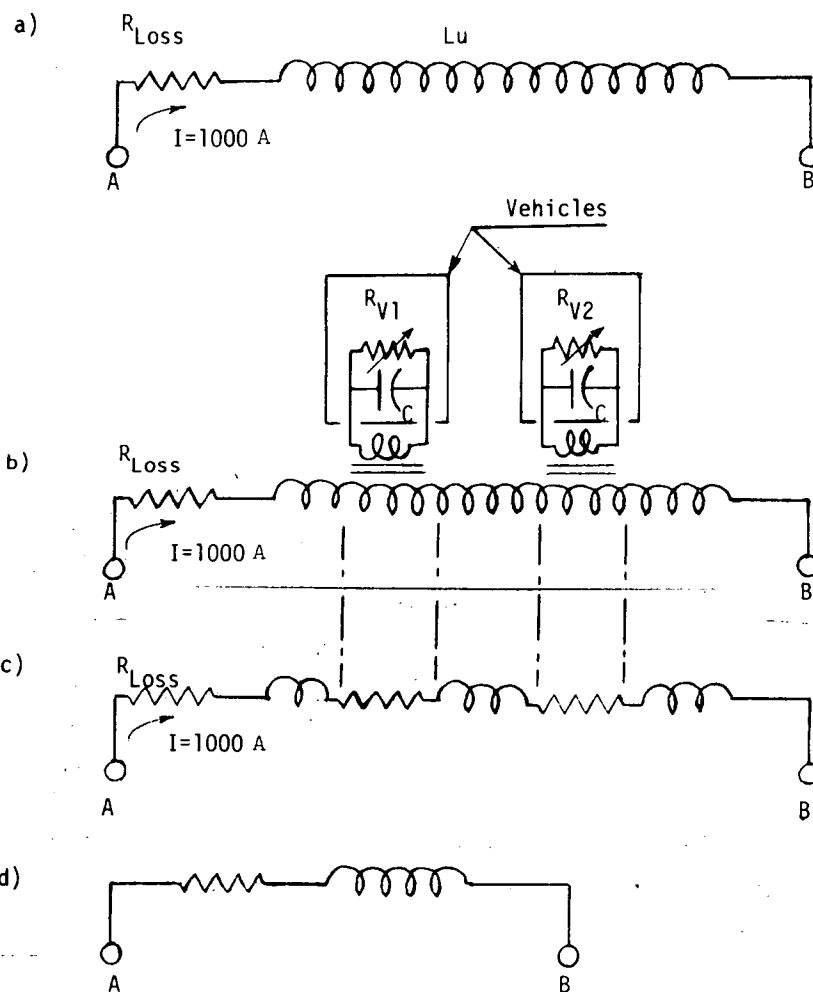


Fig. 4.7. Development of a simplified equivalent circuit for a source loop. Terminals A and B are driven by the power conditioning equipment. (XBL 774-757)

suitable for the DMET system (~2 MVA). The core losses would be higher than the losses in the other two systems, but because of its low cost and the low part count (which should translate into higher reliability), it may still be economically attractive.

Terms in Common Usage for Power Conditioning Equipment

Converter	A general term applying to common types of power conditioning equipment
Rectifier	An ac to dc converter
Inverter	A dc to ac converter
Cycloinverter	An ac to ac converter in which the output frequency is greater than the input frequency

4.3.1. Basic Design Considerations

The roadway source of the Roadway Powered Vehicle System consists of a single electrical conductor imbedded in magnetic material (see Fig. 4.2). In the model considered in this preliminary study, a current of 1000 Arms at a frequency of 180 Hz flows in the conductor. The current is regulated to be relatively constant. Each power conditioning station powers to two single-phase circuits, each consisting of two parallel lanes (e.g., one lane in each direction of traffic) as shown in Fig. 4.6. Thus, if the separation between stations is 2L miles, each station drives two source loops, each loop servicing 2L lane-miles.

Electric utilities can most conveniently provide power in a three-phase configuration at a frequency of 60 Hz. Thus, the power conditioning station has two primary functions:

1. Convert 3-phase 60 Hz power to single-phase 180 Hz power.
2. Regulate the current in the source loop to approximately 1000 A over the full range of vehicle loading.

Both the number of vehicles using a given source loop and the power absorbed by each vehicle change with time. Figure 4.7 will aid in visualizing how this affects the loop characteristics.

In Fig. 4.7(a) the loop is unloaded (no vehicles present). The predominant elements are L_u , representing the total uncoupled inductance of the loop, and R_{Loss} , representing the losses associated with the constant loop current.

In Fig. 4.7(b) two vehicles are shown on the loop. They are magnetically coupled to the loop as described earlier. The pickup of a vehicle and the portion of the source coupled to the pickup form a transformer. As described in the section on the vehicle power supply, it is convenient to compensate for the inductive parameters of the transformer with a capacitor on the vehicle. This capacitor is shown as C in Fig. 4.7(b). The variable resistors R_{V1} and R_{V2} represent the power used by each of the two vehicles.

For the moment, we assume: the turns ratio of the coupling transformer is unity; the values of R_{V1} and R_{V2} are chosen to absorb the maximum design power for automobiles of 20 kW; and the value of C is chosen to place the vehicle circuit in resonance at 180 Hz. The latter assumption allows us to represent the vehicle as a resistive load to the loop.

This leads to the equivalent circuit of Fig. 4.7(c). Here, the presence of each vehicle is represented by a resistor. It replaces the segment of uncoupled inductance that lies directly under the pickup.

The equivalent circuit of the loaded loop can be further reduced as in Fig. 4.7(d). Because of the simplifying assumptions, the loop can be represented by a single L and single R, where:

$$L = L_u - n \times \ell_u \times d$$

where ℓ_u = uncoupled inductance of loop, per unit length

L_u = total uncoupled inductance of loop

= $\ell_u \times$ total loop length

n = number of vehicles on loop

d = length of pickup on each vehicle

and

$$R = R_{Loss} + R_{coupled}$$

$$= R_{Loss} + \sum_{i=1}^n \frac{P_i}{I^2}$$

where: I = loop current
= 1000 A.

If each vehicle is an automobile drawing its maximum design power of 20 kW,

$$R = R_{Loss} + n \times (0.02 \Omega)$$

The electrical characteristics of the loop as seen by the power conditioning station are given in Table 4.5. Note that, because of the changing power factor of the load, the total loop voltage changes by only 30% from no load to maximum design load.

Thus far in this section, it has been assumed that all vehicles on the loop are drawing full power. This, of course, is only an extreme condition; in general, they can be drawing any power level between 0 and 20 kW. The detailed loop characteristics with an arbitrary number of vehicles, each drawing an arbitrary level of power, have not yet been derived. The results of the preliminary work give confidence that the loop characteristics under these conditions will be well behaved. Further investigations in this area will be part of the continuing effort.

The magnitude of roadway source current is an important circuit parameter. Using data from Table 4.5, the total impedance with no car present is:

$$\begin{aligned} Z_{Total} &= \sqrt{X_L^2 + R_{Loss}^2} \\ &= \sqrt{2.307^2 + 0.019^2} \\ &= 2.307 \Omega/\text{mile} \quad (1.43 \Omega/\text{km}) \end{aligned}$$

with 20 coupled cars on the roadway:

$$\begin{aligned} Z_{Total} &= \sqrt{X_L^2 + R^2} \\ &= \sqrt{2.268^2 + 0.78^2} \\ &= 2.398 \Omega/\text{mile} \quad (1.490 \Omega/\text{km}) \end{aligned}$$

The change is only 4%. Even with 100 cars on the roadway, a similar calculation will show the impedance change to be less than 30%. Thus for a constant voltage and varying load, the change in current would be relatively small.

Three power converter configurations were studied. One utilizes an ac to dc converter (rectifier) followed by a dc and ac converter (inverter). The ac developed by the inverter is of a different frequency from that supplied to the rectifier. Another configuration uses a cycloinverter to convert ac of one frequency to ac of another frequency, with no intermediate dc link. The third configuration uses a static frequency tripler that makes use of the third harmonic distortion in a saturated transformer core. Of these three methods, only the rectifier inverter can generate frequencies other than 180 Hz.

4.3.2. Cycloinverter System

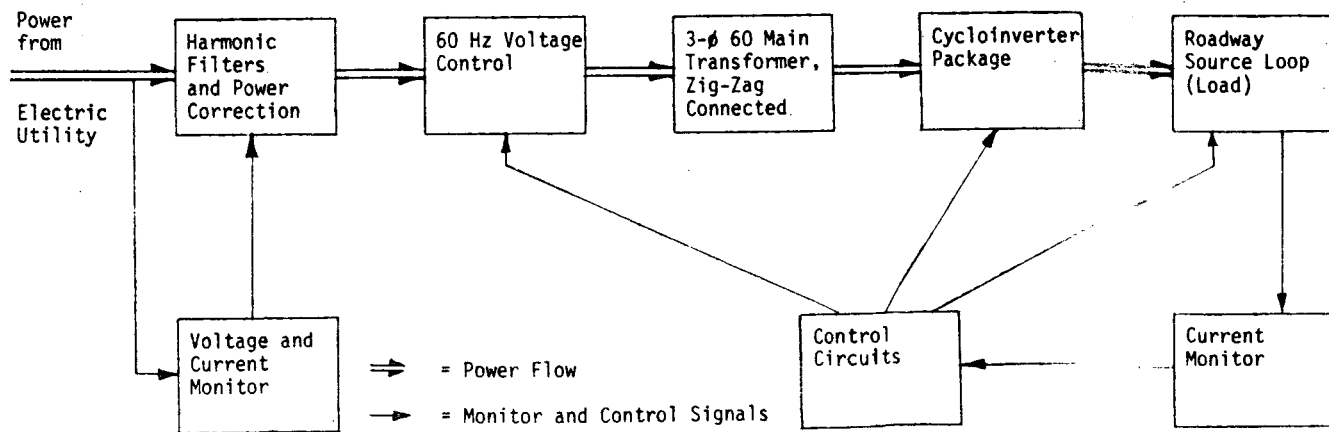
4.3.2.1. System Description. A cycloinverter transforms power supplied at one frequency into output power at a higher frequency. In particular, it is suitable to transform power from 3-phase 60 Hz to single phase 180 Hz.

The major components of a cycloinverter system are shown in Fig. 4.8. Power is delivered from the utilities on the left of the figure and to the roadway source loop on the right. The usual cycloinverter induces large harmonic currents in its power source. This is objectionable to power companies and could cause serious interference with communication circuits. Harmonic filters at the input can reduce the harmonics to negligible levels. The 60 Hz voltage control can be achieved by a variable series reactance, by an inductrol, by tap-changing on the main transformer, or by SCR phase control. The 60 Hz main transformer is zig-zag connected to eliminate third harmonic line currents (which would flow with wye-delta, wye-wye or delta-delta configurations). The cycloinverter package contains the SCR's and firing circuits.

4.3.2.2. Detailed Operation. Figure 4.9 shows the basic circuitry of a cycloinverter package. In order to present a more nearly balanced load to the main transformer, two "half-wave" cycloinverters, each

Table 4.5. Electrical Characteristics of Source Loop. All Quantities Refer to One Lane-Mile (1.6 lane-km) of Powered Roadway. Frequency is 60 Hz; Loop Current is 1000 A; Coupled Vehicles Draw 20 kW.

Number of Vehicles Absorbing 20 kW, n	0	5	20	50	100
a) In terms of equivalent circuit elements					
Loop inductance L (mH)	2.039	2.030	2.001	1.943	1.846
Loop reactance X_L (Ω)	2.307	2.296	2.263	2.198	2.088
Loop losses R_{Loss} (Ω)	0.019	0.024	0.038	0.065	0.112
Vehicle power $R_{coupled}$ (Ω)	0	0.05	0.40	1.0	2.0
Total resistance R (Ω)	0.019	0.074	0.78	1.065	2.112
b) In terms of power quantities					
Power coupled to vehicles (kW)	0	100	400	1000	2000
Voltage to drive source loop (V)	2307	2299	2304	2442	2970
Power factor of source loop	0.008	0.054	0.190	0.0441	0.730
Power to drive loop (kW)	19	124	438	1065	2112



(XBL 774-758)

Fig. 4.8. A block diagram showing flow of power, monitoring, and control in a cycloinverter power conditioner.

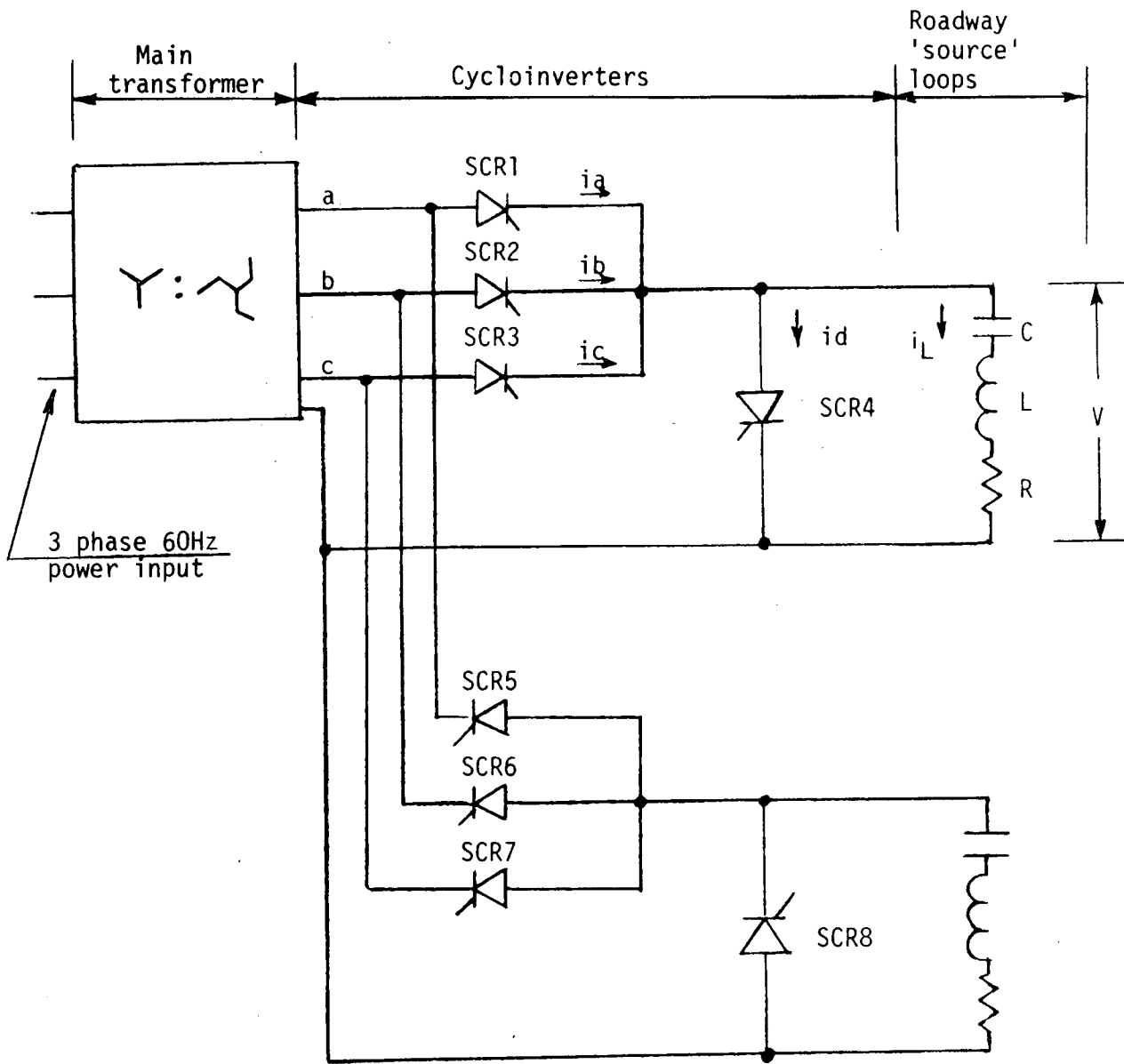


Fig. 4.9. Simplified schematic of a dual cycloinverter driving two roadway source loops. (XBL 774-759)

driving a source load, are powered by the transformer. As shown in Fig. 4.6, each source load consists of $2L$ lane miles of source. The characteristics of the source load are represented by R and L . As shown in Table 4.5, L the effective inductance of a source loop, is relatively constant with changing traffic load. The effective resistance R changes in accordance with the traffic load. It represents the power absorbed and used by the vehicles. The capacitor C is added to provide the mechanism for current commutation, which is essential to the operation of this configuration of cycloinverter. The value of C is chosen so that L and C resonate at some frequency greater than 180 Hz.

The detailed operation is now described. For simplicity, we concentrate only on the upper half of Fig. 4.9, which uses SCR's 1-4. The waveforms of Fig. 4.10 correspond to this part of the circuit. The lower half of Fig. 4.9, which works in a similar manner, is included to provide a balanced load on the transformer.

The SCR 1 is fired at time t_1 in Fig. 4.10. Time t_1 must be during the positive excursion of voltage V_{a-n} (voltage of phase a with respect to neutral, n). Because of the nature of the L - R - C load circuit, the current i_a flows as a pulse; the current returns to zero at time t_2 . This leaves the capacitor C charged to a voltage, the value of which is close to the average value of V_{a-n} during the interval $t_1 - t_2$. The voltage V across SCR 4 is, therefore, positive. At t_3 , SCR 4 is triggered. As a result another pulse of current flows between t_3 and t_4 , using energy previously stored in C . The pulse carries approximately the same charge as the pulse $t_1 - t_2$, but flows in the opposite direction through the load. Thus, at t_4 a complete cycle of alternating current has flowed through the load. The period of this cycle is controlled (by regulating the triggering of the SCR's) to be $1/180$ sec.

At time t_5 , a similar process begins, except that SCR 2 is triggered, and the current is supplied by V_{b-n} .

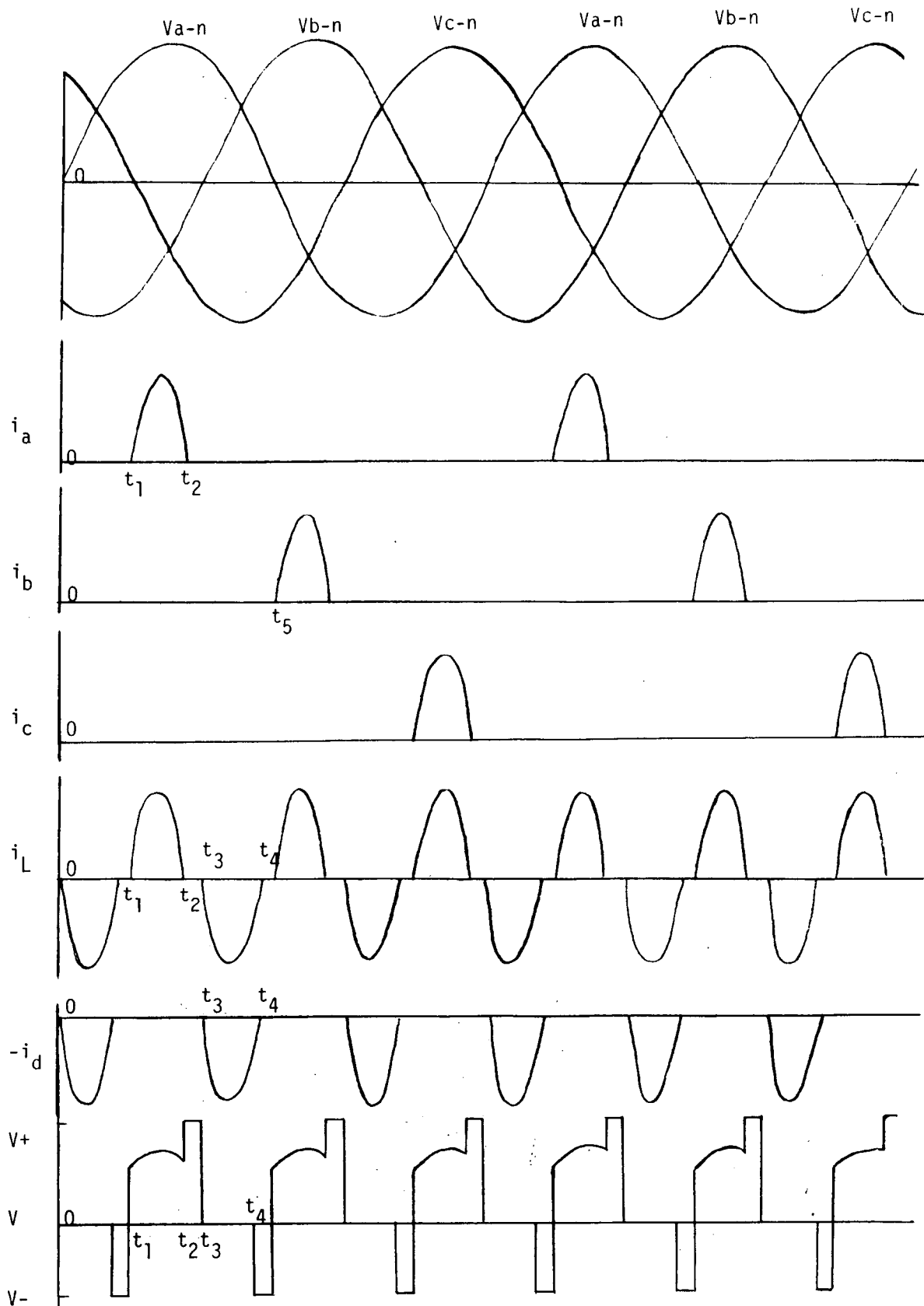


Fig. 4.10. Waveforms at various points in cycloconverter (upper cycloconverter, Fig. 4.9). (XBL 774-760)

Each 1/60 sec, the SCR triggering sequence is SCR 1-SCR 4-SCR 2-SCR 4-SCR 3-SCR 4. This has resulted in three complete cycles of current through the load, i.e., a frequency of 180 Hz.

It is essential that the current i_L from a previous pulse decay to zero before the next pulse is started, otherwise a short circuit of the main transformer through two SCR's will result. Thus, for example, there must be a short interval between t_2 and t_3 .

Figure 4.4 shows that, for a constant load current, the effective 60 Hz input voltage must change to accommodate the electrical load changes caused by changes in traffic loading. The amplitude of the load current can be regulated by controlling the phase angle of supply voltage at which SCR's 1, 2, and 3 are triggered. For example, t_1 can occur at any phase of V_a-n between 0° and 180° . This is a larger range than with other cycloinverter circuits, and results from the fact that no current flows in the transformer legs during the negative voltage excursions. The load current amplitude can also be controlled by changing the 60 Hz voltage applied to the input of the main transformer.

4.3.2.3. Model Verification. Figure 4.11 shows the circuit of a low-power model of the cycloinverter that was used to verify its operation. Typical waveforms observed are shown in Fig. 4.12. As shown in Fig. 4.13, the load current can be controlled by regulating the angle of input voltage at which the SCR's are fired. Figure 4.14 shows waveforms of current as the triggering phase α is varied. In Figs. 4.11, 12, 13, and 14, the Q of the LRC load was approximately 23 ($Q = \omega_0 = 2\pi \cdot 180$).

4.3.2.4. Power Factor Correction and Harmonic Suppression. The price paid to the utility for electric power can be minimized by properly conditioning the power drawn from the utility system. In particular, the power factor should be maintained close to unity, and harmonics in the current should be held to a low level.

The power factor can be controlled in at least two ways--by the firing angle of the SCR's in the cycloinverter or by power factor correction capacitors. As noted in Table 4.5, the power factor of the 180 Hz source loop will vary widely from no load to full load. It should be emphasized that, because the cycloinverter is placed

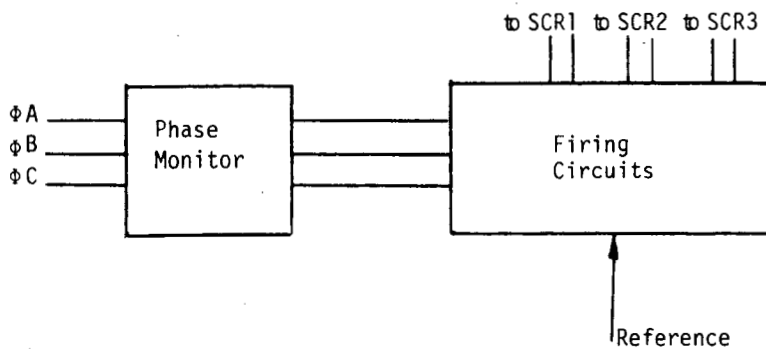
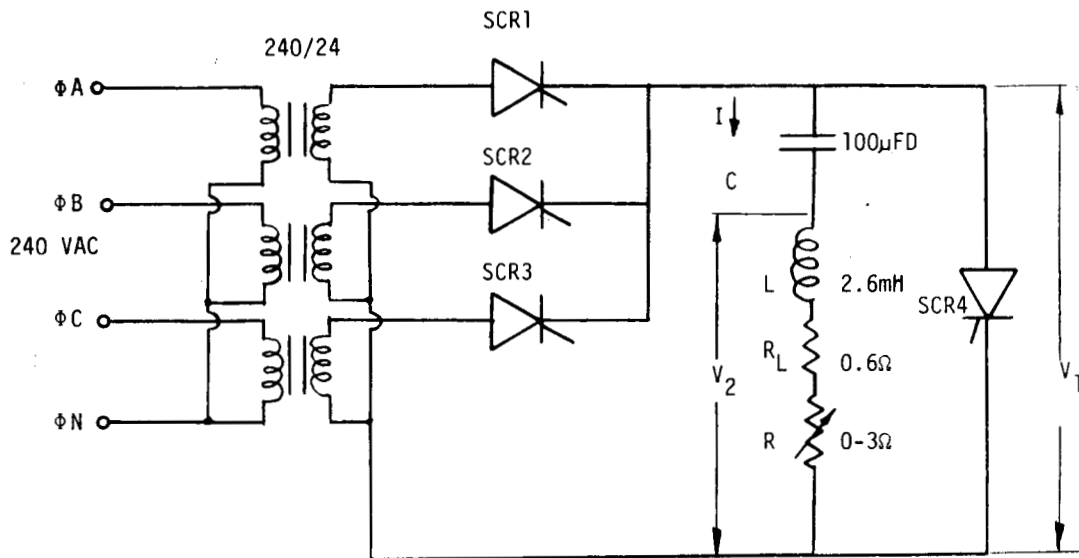


Fig. 4.11. Circuit of a low-power model of cycloinverter. (XBL 774-761)

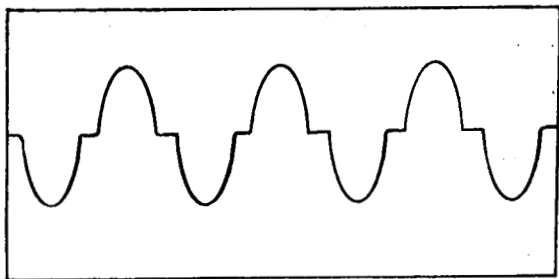


Fig. 4.12. Typical current waveforms obtained in low-power cycloinverter model. (XBL 774-762)

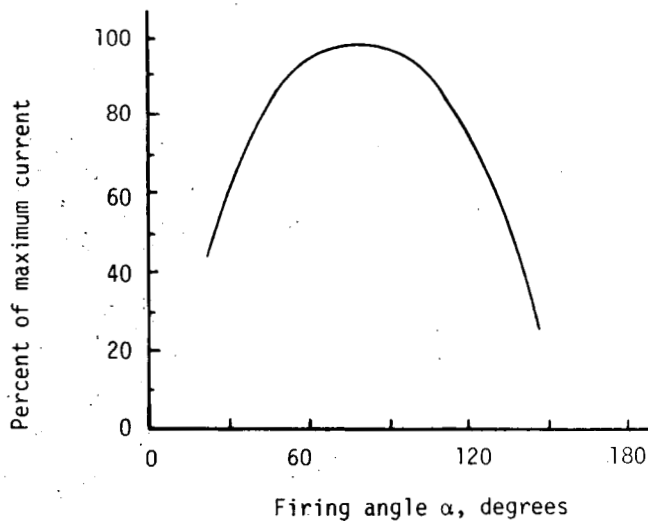


Fig. 4.13. Observed relationship between load current I_L and SCR firing angle α . Firing angle is the phase of voltage with respect to neutral (e.g., V_{a-n}) when the SCR is fired (e.g., t_1 in Fig. 4-10). (XBL 774-763)

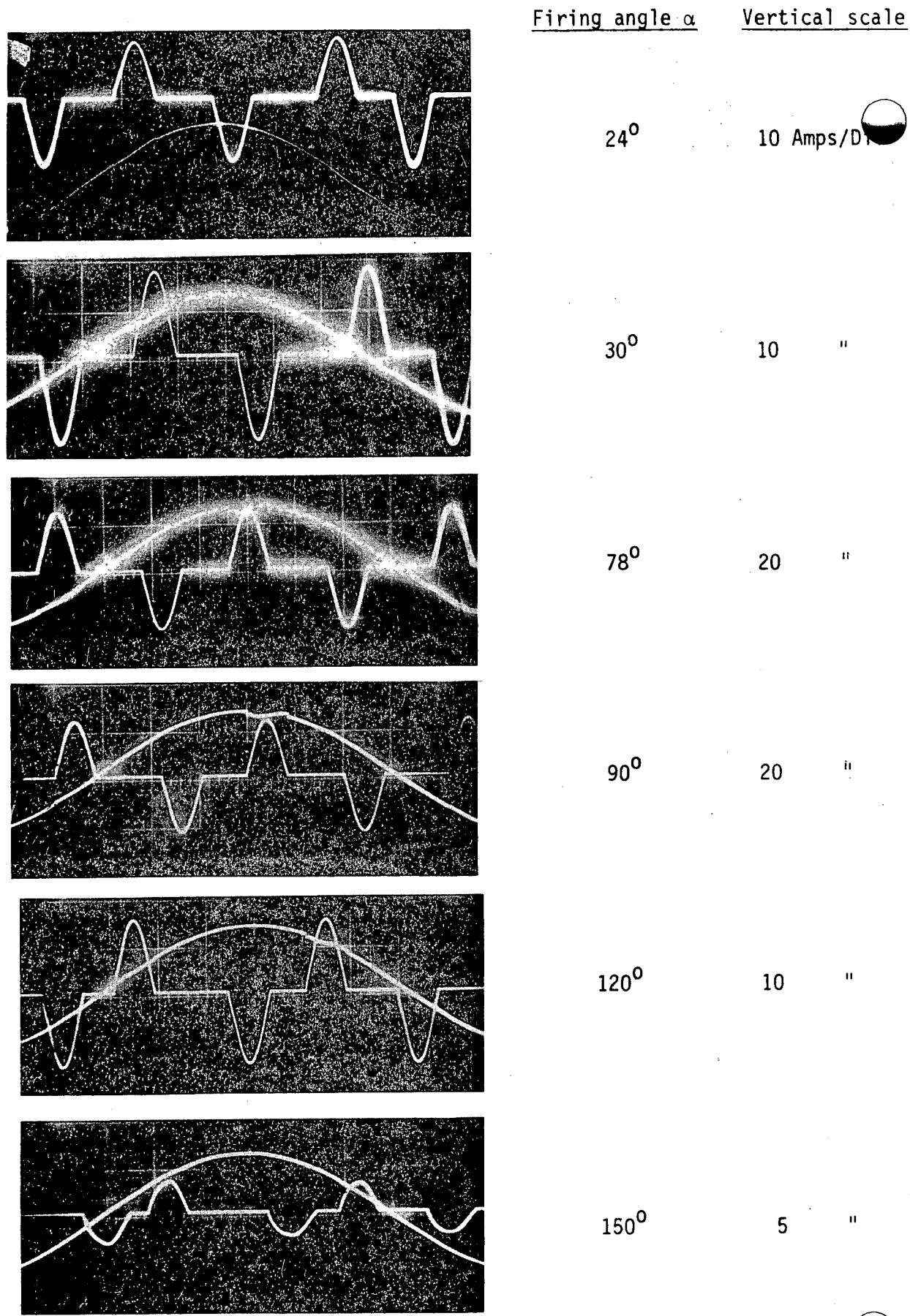


Fig. 4.14. Observed waveforms of load current I_L in low-power model of cycloinverter for six values of firing angle α . Horizontal scale is approximately 1.3 msec/div. A 60 Hz time reference trace is included in photos. (XBL 774-764)

between the source loop and the electrical utility, the power factor variation seen by the utility can easily be controlled to be small.

Since current flows for a portion of each half-cycle input power in each leg of the input transformers, harmonics are inevitably generated. The third harmonic current is cancelled by using the zig-zag connection for the input transformer. Computer analyses were done on calculated line current waveforms at the primary of the input transformer to determine the amplitudes of other harmonics. A typical result is shown in Table 4.6. This shows that harmonic filters will need to be provided as shown in the block diagram, Fig. 4.8.

4.3.3. Rectifier-Inverter System

Figure 4.15 shows a block diagram of a rectifier-inverter form of power conditioner. The significant differences with respect to the cycloinverter (Fig. 4.8) are the rectifier and inverter blocks. Input 60 Hz power is converted to dc by the rectifier; it in turn is converted to 180 Hz ac by the inverter. The rectifier can be of conventional design as shown in Fig. 4.16. The half-bridge inverter is made up of two chopper circuits, one of which is shown in detail in Fig. 4.17. The circuit operation is now described with reference to the waveforms of Fig. 4.18.

At t_0 , capacitor C_1 has been charged to voltage V , through resistor R_1 . At t_0 SCR 1 is triggered. Its current i_{SCR1} rises to some maximum value determined by the load. At t_1 , force commutation is started by firing SCR 2. C_1 , L_1 , and SCR 2 form an oscillatory circuit with C_1 , discharging through SCR 2. At t_2 , i_{SCR2} goes to zero and SCR 2 turns off. The current through the capacitor now swings positive and D_3 turns on. At t_2 , C_1 , L_1 , and D_3 form a shunt path for current flowing through SCR 1 so that the load current is diverted from SCR 1. At t_3 , i_{SCR1} has gone to zero and diode D_1 turns on, thus commuting SCR 1. The voltage across C_1 rises to a maximum voltage at t_5 . Then D_2 turns on, shunting current from D_3 . At t_6 , i_{C1} has decayed to zero and v_{C1} has discharged to V through R_1 . The load current decays through D_2 and that is the end of the commutation cycle. The circuit is now ready for the negative cycle of operation, which is

Table 4.6. Harmonic Content of 60 Hz Line Current drawn by Cycloinverter Under Typical Conditions, Expressed as Fraction of Fundamental Current Amplitude

Harmonic	Amplitude
Fundamental	1
Third	0*
Fifth	0.57
Seventh	0.28
Eleventh	0.058
Thirteenth	0.061
Seventeenth	0.033

* Cancelled by zig-zag connection of main transformer.

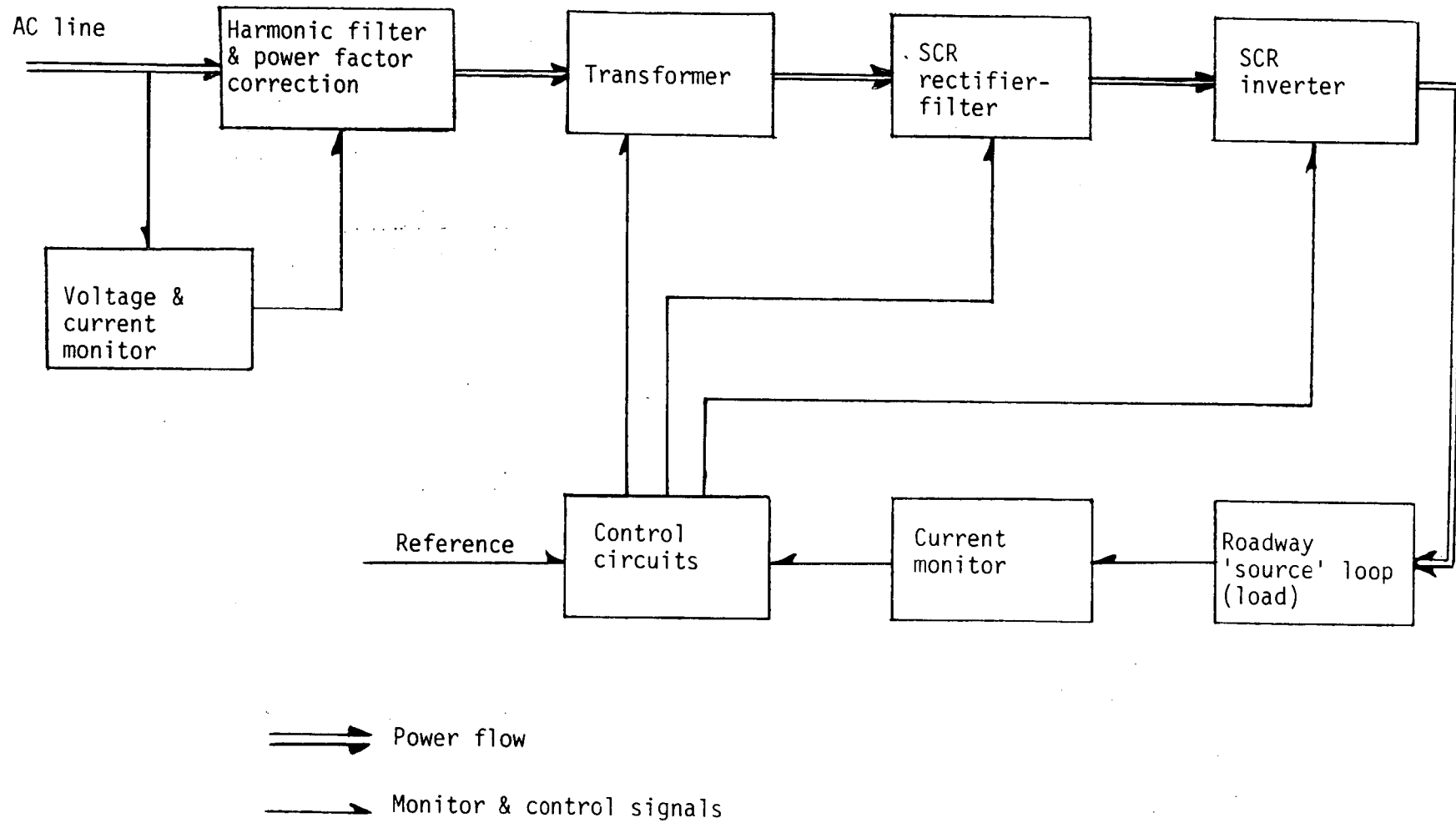


Fig. 4.15. Rectifier-inverter power system. (XBL 774-765)

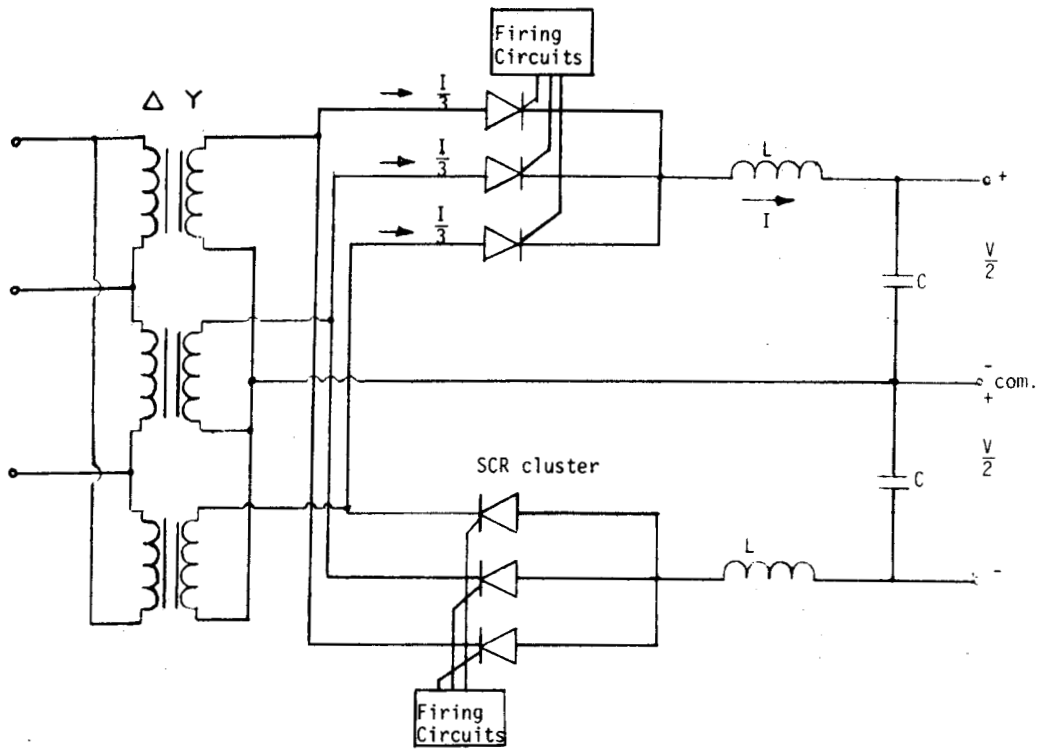


Fig. 4.16. Rectifier power supply and filter. (XBL 774-766)

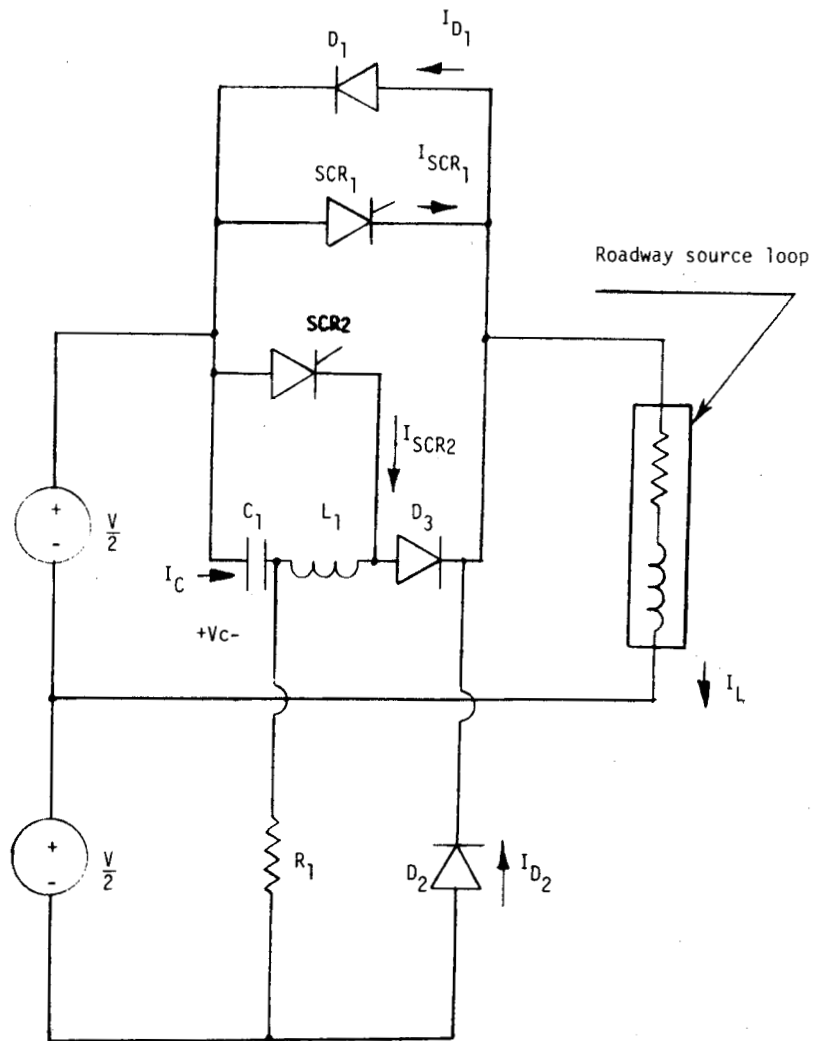


Fig. 4.17. Detail of chopper circuit. (XBL 774-767)

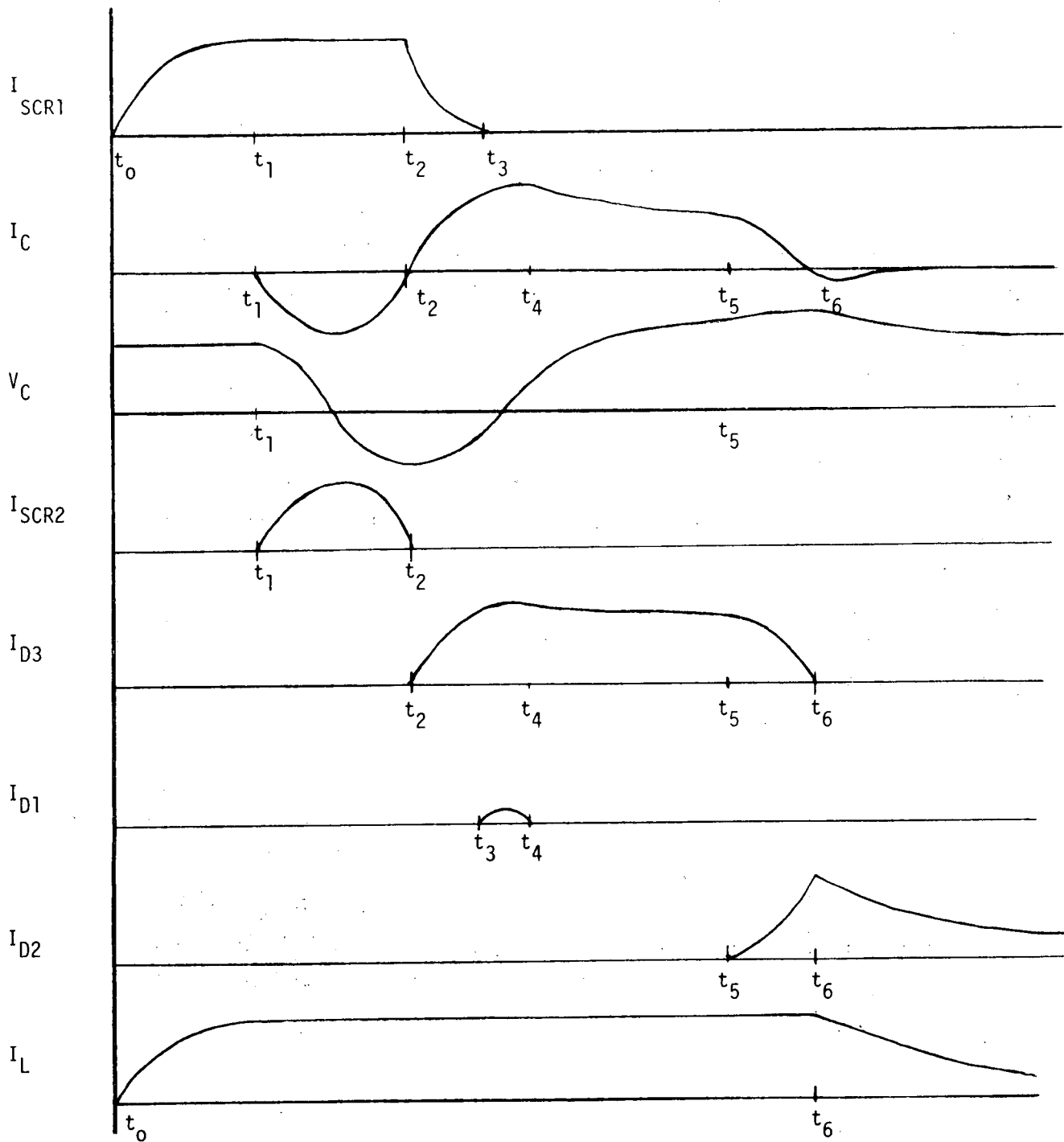


Fig. 4.18. Circuit phase relationships. (XBL 774-768)

identical to the operation outlined above. The negative lobe of current is supplied by an identical circuit with reversed polarity components.

The operation of a rectifier-inverter system, as with the cycloinverter, results in the generation of harmonic line currents. Typical values are given in Table 4.7.

4.3.4. Static Frequency Tripler

Available information on the static frequency tripler is limited. Its cost in the 1-2 MVA rating required by the DMET system may be advantageous. The static tripler uses a saturated transformer core to generate a large third harmonic content in the output waveform. This harmonic can be used to obtain power at third harmonic frequency. As a result, this type of power converter has a lower part count and maintenance cost, but these advantages are obtained at the expense of higher losses. Further study is needed to evaluate its technical feasibility and the economic tradeoffs.

4.3.5. Cost Estimates

Preliminary cost estimates for the cycloinverter and the rectifier-inverter power conditioners have been made. These are based on estimated present costs for the major components of the respective systems. These costs include only the basic converter. They do not, for example, include the cost of buildings or installation. They should be used primarily to compare the relative costs of the two converters studied.

The costs are tabulated for a power supply of 2 MW rating. This is sufficient to power two lane-miles of traffic when manual vehicle controls are used (50 cars per lane mile, maximum), or one lane-mile of traffic when fully automatic vehicle controls are used (100 cars per lane mile).

Table 4.7. Harmonic Content of 60 Hz Line Current Drawn by Rectifier-Inverter Under Typical Conditions, Expressed as a Fraction of Fundamental Current Amplitude.

Harmonic	Amplitude
Fundamental	1.0
Fifth	0.20
Seventh	0.14
Eleventh	0.091
Thirteenth	0.077
Seventeenth	0.059

Cycloinverter Cost Estimate

Main transformer	\$ 27,000
60 Hz switchgear	20,000
Cycloinverter package	20,000
Resonating capacitors	16,000
Line filters and power factor correction	20,000
Monitoring and control	15,000
Total	\$118,000 (2 MW)

Notes: The cycloinverter has some costs that are specifically incurred because of its characteristics. For example, the transformer must be of sufficient rating to absorb the harmonic currents. The multiple windings on the transformer legs to achieve the zig-zag connection add to the cost. The large harmonic line currents require filters. Control of constant current by means of SCR phasing is assumed.

Rectifier-Inverter Cost Estimate

Main transformer	\$ 20,000
Switchgear	20,000
Rectifier	14,400
L-C filter	40,000
Inverter	28,000
Harmonic filters and power factor correction	20,000
Control and monitoring	20,000
Total	\$162,400 (2 MW)

Notes: The rectifier-inverter presents a more straightforward control problem. A substantial cost is for filtering circuits in the dc portion.

4.4. THE DMET VEHICLE

4.4.1. Electrical System

Every roadway-powered vehicle will need on-board facilities to enable it to extract and regulate power from the roadway. This section summarizes the results of some preliminary investigations of the on-board vehicle circuitry for this purpose. A detailed

investigation will be required to optimize characteristics of the vehicle power system such as: interaction with the drive of the vehicle; cost; efficiency; weight; etc. The work reported here was oriented toward a basic, immediate goal of verifying that the vehicle power system is physically realizable and that no major problems are evident.

4.4.1.1. Assumptions. The following assumptions were used in the preliminary investigation:

1. The circulating current in the roadway power source is 1000 A at a frequency of 180 Hz. This is effectively the one-turn primary of the coupling transformer.

2. A 5 ft length of coupling has magnetizing inductance of 7.96×10^{-6} H and a leakage inductance of 1.33×10^{-6} H, both referred to the source. Core and conductor losses are represented by $5.45 \times 10^{-5} \Omega$ and $2.588 \times 10^{-5} \Omega$, respectively.

3. The maximum power required by the vehicle is 20 kW.

The following conclusions about an equivalent circuit can be drawn from the assumptions:

1. To absorb 20 kW, the vehicle must present a resistive load to the primary of 0.02Ω ($1000 \text{ A}^2 \times 0.02 \Omega = 20 \text{ kW}$).

2. The magnetizing inductance has a reactance of only 0.01Ω at the source frequency of 180 Hz.

3. It therefore appears expedient and necessary to compensate (partially resonate) the magnetizing inductance with a capacitor in order to present a resistive load of 0.02Ω to the source. This conclusion is reinforced by the result of a computer study using a simplified (no loss) model. The input power was calculated at different capacitance values. The result, as plotted in Fig. 4.19, clearly shows the resonance effect. The maximum value of input power occurs with an optimum capacitance value.

4.4.1.2. Equivalent Circuit. This leads to the equivalent circuit shown in Fig. 4.20. For simplicity, all values are referred to the source. Losses in coupling transformer and capacitor are neglected. The 1000 A current generator represents the (constant) 180 Hz current flowing in the source. The magnetizing (L_m) and

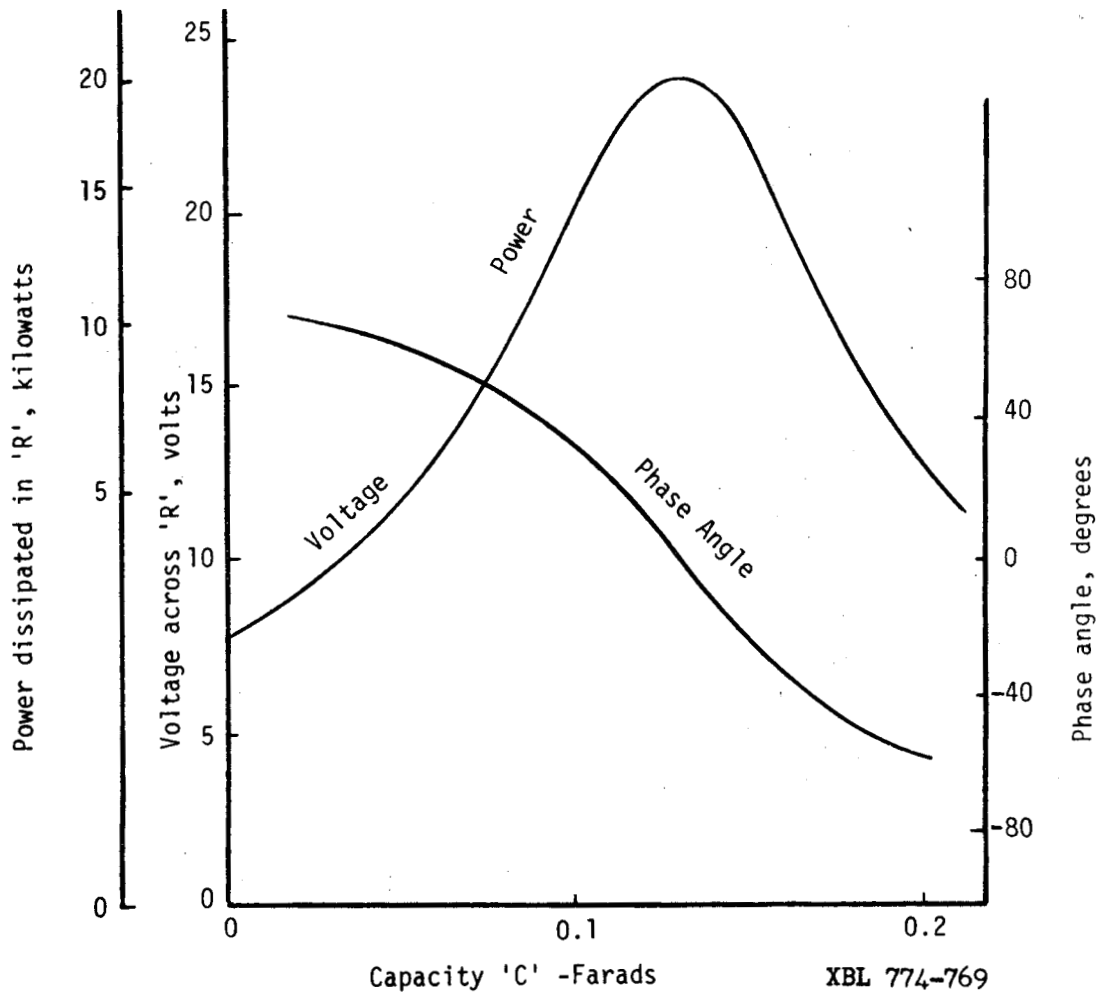


Fig. 4.19. This figure shows some computed characteristics of a network similar to Fig. 4.24, which represents on-board vehicle's power and control circuits. The voltage across the resistor R, and the power absorbed by R as a function of the compensating capacity C are shown. Also shown is the phase angle of the impedance presented to the source (see Fig. 4.7). (XBL 774-769)

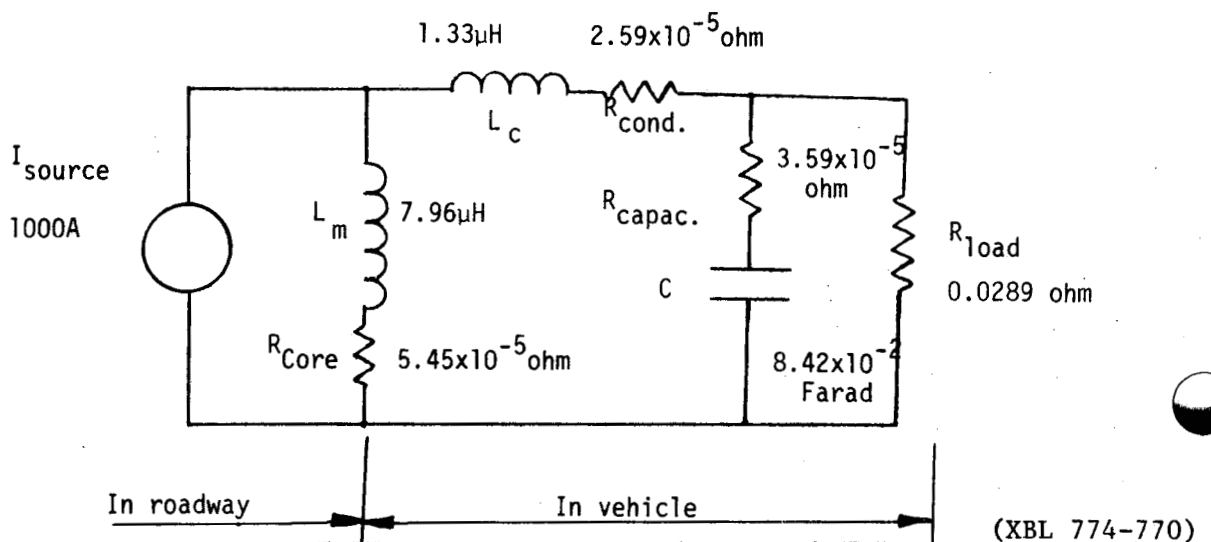


Fig. 4.20. Equivalent circuit of the Roadway Powered Vehicle System. (XBL 774-770)

leakage (L_e) inductance are characteristic of the coupling; transformer values are taken from the analysis in Section 4.1. The capacitor C is the element added to compensate for the inductance of the coupling. The resonance value can be calculated from

$$C = \frac{1}{(2\pi f)^2 \cdot (L_m + L_e)} \quad ;$$

$$= 0.08416 \text{ Farad (referred to primary); the loss}$$

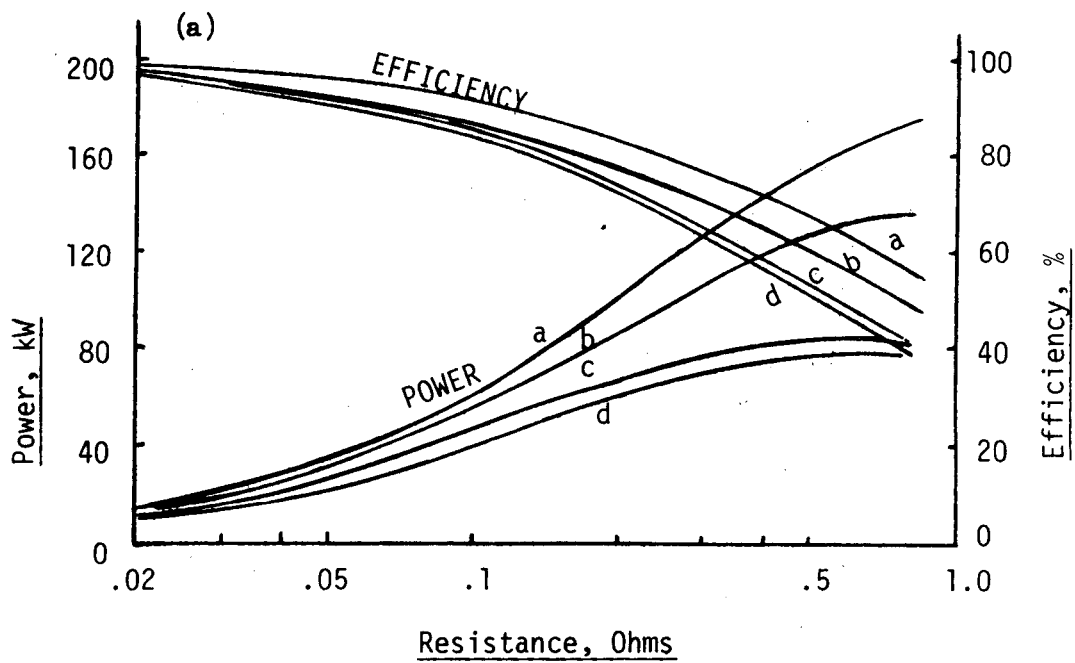
$$\text{in the capacitor is represented by a resistor}$$

$$\text{(R capacitor) of } 3.59 \times 10^{-5} \Omega$$

The equivalent circuit of Fig. 4.20 was used to calculate the power transferred and the overall efficiency as load resistance varied. Similar studies were also made of the cases in which the air gap was increased to 1-1/2 in. (3.8 cm), or the pickup was offset by 2 and 4 in. (5 and 10 cm) with respect to the source. It was found that when the compensating capacitor remained unchanged, the maximum power that could be coupled was sometimes less than the required 20 kW. However, the power that can be coupled exceeds 20 kW for all positions studied when the capacitance is readjusted to exactly compensate the inductance. This points out the need for dynamic capacitance compensation. Also note that with this compensation, the efficiency exceeds 93% when 20 kW is transferred, and the required resistance changes only slightly. The result as plotted in Fig. 4.21 also indicates the power increase with increasing load resistance, which is typical of a constant current network.

4.4.1.3. Power Level Control. Most familiar power control situations involve constant voltage (low impedance) sources. A typical controller for such a situation is shown in Fig. 4.22. Clearly, as the duty cycle of the switch decreases, the power absorbed by R_{Load} decreases, and R_{eff} increases.

However, the constant current nature of the circulating source current in the highway presents a special situation. If the generator in Fig. 4.22 were a constant current generator, then as R_{eff} increases, the power absorbed increases as shown on Fig. 4.21. Thus, the technique of Fig. 4.22 appears not to be applicable.



	Offset inches (cm)		Air gap inches (cm)	
a	0	0	1	2.5
b	2	5	1	2.5
c	4	10	1	2.5
d	0	0	1 1/2	3.8

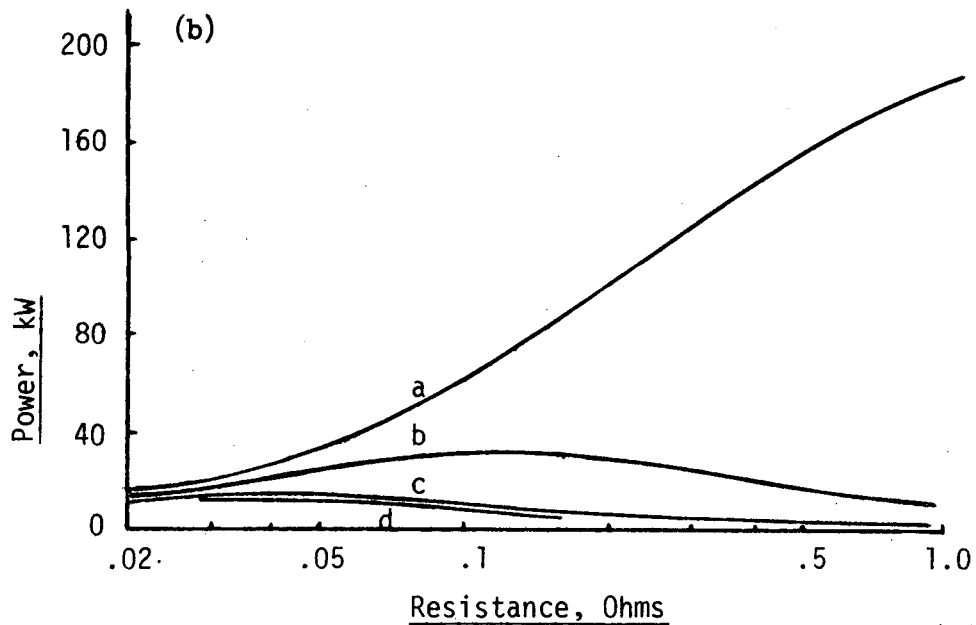


Fig. 4.21. (a) Power coupled vs resistance with optimum compensation; (b) power coupled vs resistance with fixed compensation. (XBL 774-771)

At the moment, we see two basic methods of power level control:

1. The switching regulator that uses switches to develop short circuits, rather than open circuits. Figure 4.23 is an example. Here, the power absorbed and the value of R_{eff} decrease as the duty-cycle of the switch is increased.

2. Control by capacitor. The second method involves controlling the value of C in Fig. 4.20. As shown in the graph of Fig. 4.19, for a constant value of R , the power absorbed can be controlled by changing the value of C , i.e., by detuning the circuit. For example, four capacitors whose values are proportional to 1, 2, 4, and 8 could give 16 levels of power as various combinations of these capacitors are switched into or out of the circuit.

4.4.1.4. A Specific Equivalent Circuit. Figure 4.24 is the same as the equivalent circuit of Fig. 4.20; but with the values for components, currents, and voltages when the circuit is tuned to resonance, and when 20 kW are being absorbed by the R . "Iron" losses and other parasitic losses are ignored. Again, the values in Fig. 4.24 are all referred to the source of the vehicle-highway coupling. They would also apply to the situation where the pickup has a single turn. In practice, the pickup would have a number of turns selected to give a convenient voltage for the vehicle's motor. Figure 4.25 shows the estimated situation when the pickup/source turns ratio is 5, giving a load voltage in the region of 120 V.

4.4.1.5. Further Work. The work on this phase of the project is still in a preliminary state. It has gone far enough to show that there are no fundamental difficulties. Clearly, much detailed work remains to be done.

In the future, the design will be refined to include the details of the motor and power level regulator. The nature of the driver's control and reaction will be considered. Provision for recharging the energy source (batteries) carried in each vehicle will be investigated.

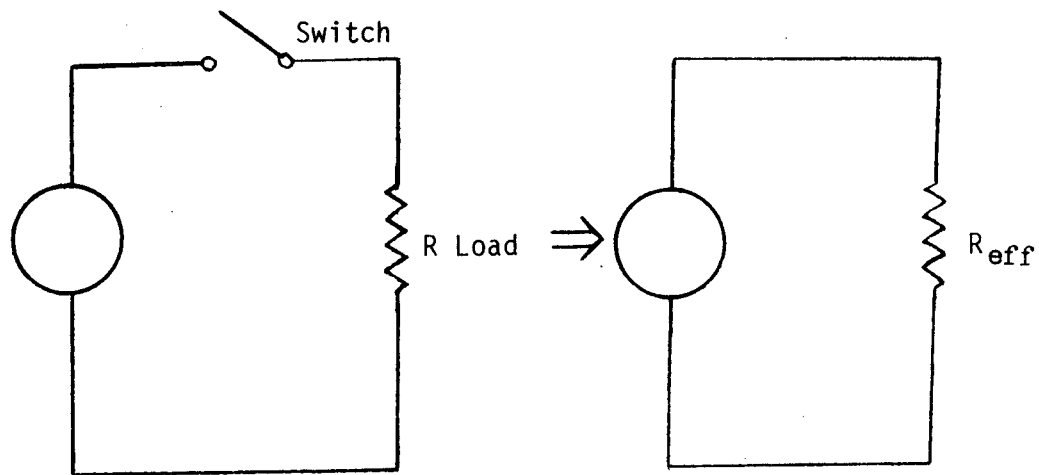


Fig. 4.22. Typical controller for constant voltage (low impedance) sources. (XBL 774-772)

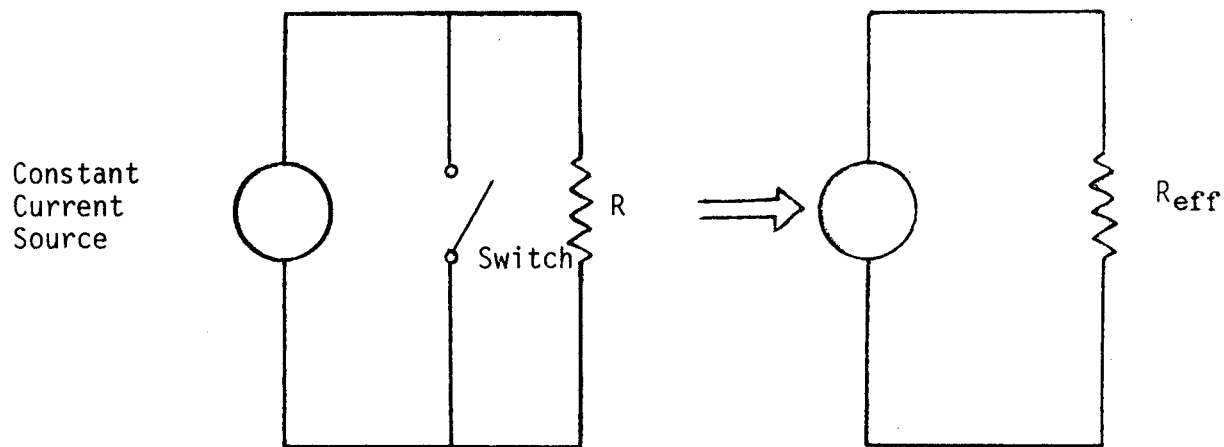


Fig. 4.23. Example of a switching regulator using switches to develop short circuits, rather than open circuits. (XBL 774-773)

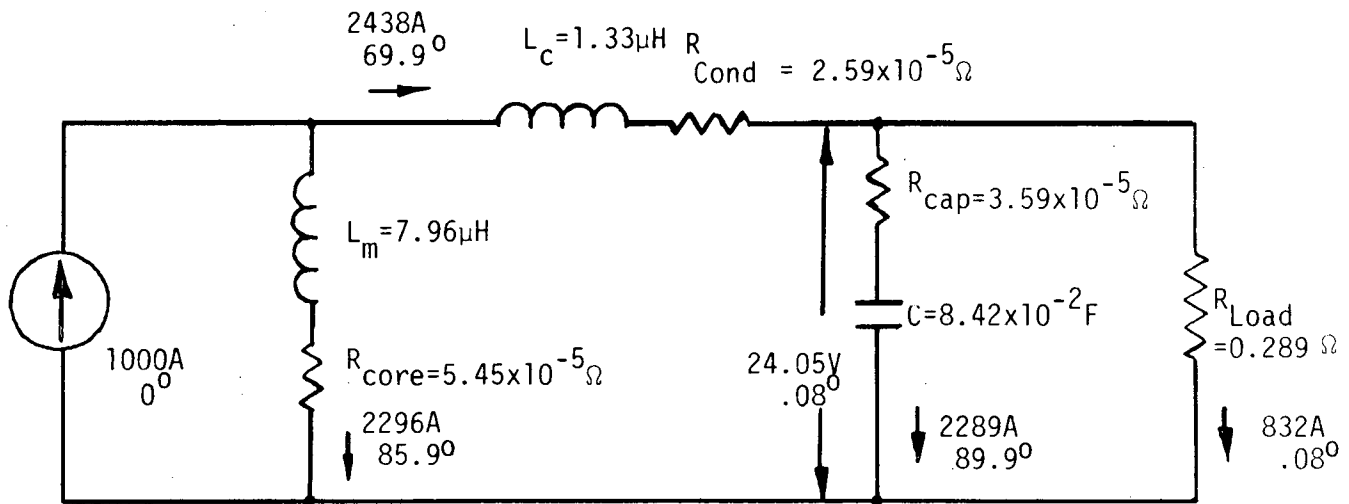


Fig. 4.24. Same equivalent circuit as Fig. 4.20, but with values for components, currents, and voltages when the circuit is tuned to resonance, and when 20 kW are being absorbed by the R. (XBL 774-774)

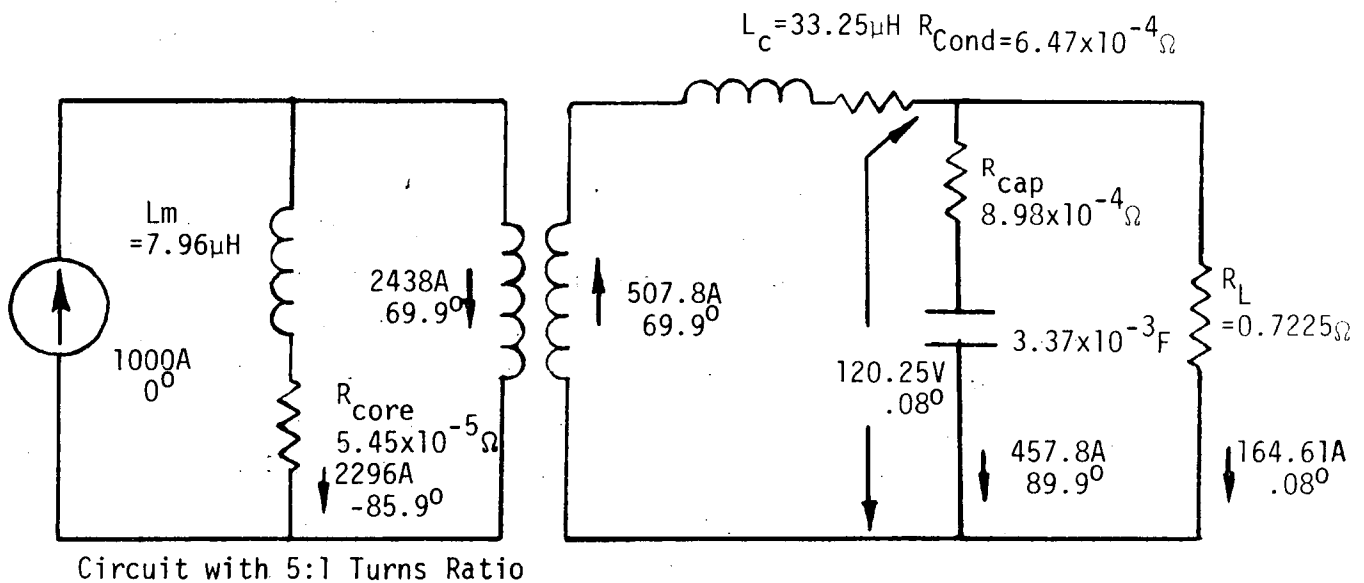


Fig. 4.25. Estimated situation when the pickup/source turns ratio is 5, giving a load voltage in the region of 120 V. (XBL 774-775)

4.4.2. Vehicle Mechanical Design

In this section, some design concepts for a vehicle compatible with the powered roadway system are discussed. The vehicle is capable of operating from two sources of power. First, it contains a pickup for obtaining power from the powered roadway. This gives it the capability for traveling unlimited distances on the powered roadway system. Secondly, it contains an energy storage pack. This enables the vehicle to travel on nonpowered sections of roadway (e.g., residential streets) for short trips or for reaching the powered roadway.

Table 4.8 contains a summary of the specifications and characteristics of such a vehicle, as it is presently conceived. Note that this design study does not exactly match the characterization in Section 5, which was made consistent with the work of other investigators.

Figure 4.26 is a conceptual design of the chassis and running gear of a vehicle compatible with the system. This arrangement locates the 500lb (227 kg) energy storage pack over the front suspension, and the traction motor and transmission, incorporated in a "De Dion" arrangement in the rear suspension. The frame is a simple "ladder," the longitudinals of which are centered below the normal position of the driver and front passenger. The frame would include insulated joints to prevent parasitic induced currents.

The region between longitudinals provides an unobstructed space for stowing the pickup. The pickup is raised and lowered by a powered actuator. In the lowered position the pickup rests on supports provided by beams between the front wheels and the rear wheels. The support links are designed with a "lost motion" so that the pickup can follow the wheels when lowered, and yet will be lifted parallel to the body for retraction. Although this suspension will add unsprung weight to the wheels and thus reduce ride quality, it is unlikely to be a serious problem since this operational mode occurs only on freeways or arterials of good surface quality.

The vehicle's motor is indicated as being a dc traction motor, chopper controlled. This is a proven technology with the capability of regenerative recovery of some of the vehicle's kinetic energy. It is likely that the economics of ac motors with available frequency

Table 4.8. Specifications for a Passenger Vehicle Compatible with the Powered Roadway System.

Wheelbase	95 in. (241 cm)
Maximum capacity, passengers	5
Weight	
Body, chassis and drive train	1450 lb (658 kg)
Energy storage pack	500 lb (227 kg)
Pickup and supports	250 lb (113 kg)
Unladen total weight	2200 lb (999 kg)
Power system	dc output, ac input
Propulsion power control	chopper
Guidance	manual steering
Minimum ground clearance*	6 in. (15 cm)
Energy Storage (at $13 \frac{\text{Wh}}{\text{lb}}$, or $29 \frac{\text{Wh}}{\text{kg}}$)	6.5 kWh
Maximum power output from energy storage	20 kW
Coupled power, maximum	20 kW
Propulsion power	See Fig. 4.27
Drive train	
Motor--power, 1 h rating, hp (kW)	39 (29)
Motor--type	dc
Motor--maximum rpm	8000
Motor--weight	80 lb (36 kg)
Transmission ratio, high gear	3.5
low gear	5.2
Magnetic forces on pickup	
Vertical	161 lb (73 kg)
Centering	negligible
* Pickup retracted.	

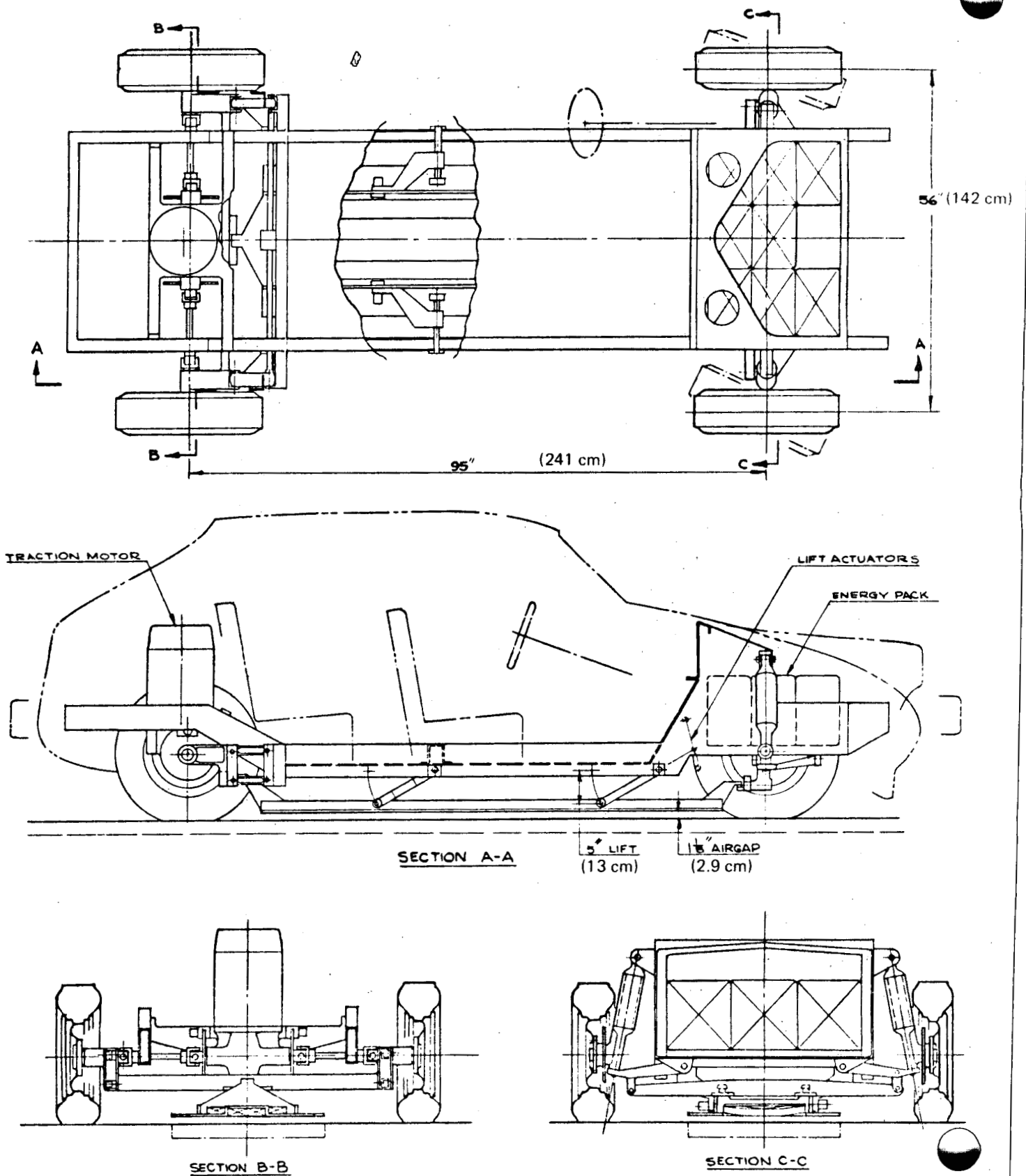


Fig. 4.26. Conceptual design of the chassis and running gear of a vehicle compatible with the system. (XBL 774-776)

inverters will improve with time. The motor size would be reduced with the ac system, at the expense of bulkier propulsion electronics.

The propulsion power requirements of the vehicle can be expected to approximate those shown in Fig. 4.27.

The size of the energy pack chosen for the conceptual design provides 6.5 kWh of stored energy, using conventional lead-acid batteries. Several considerations were involved in this design.

1. The pack would provide off-system range adequate for the needs of the typical metropolitan resident.
2. The availability of improved batteries or flywheels can be expected in the near future, which will extend the range and performance of the vehicle without adding to its weight.
3. The pack's rating is flexible in that the forward compartment would accept more batteries, and additional battery storage space is available in the rear of the vehicle; dividing the weight of added pack between front and rear would be desirable in order to maintain the original weight distribution. In this manner, the amount of energy storage can be matched to the individual user's needs.

The energy storage system used should be the subject of further study. The duty cycle of the system is quite different from battery-only vehicles. Energy storage systems that tend more toward good performance at higher power density than the usual lead-acid traction battery may be more suitable for use in roadway-powered vehicles, where freeway passing and entry involve short periods of duty at high power.

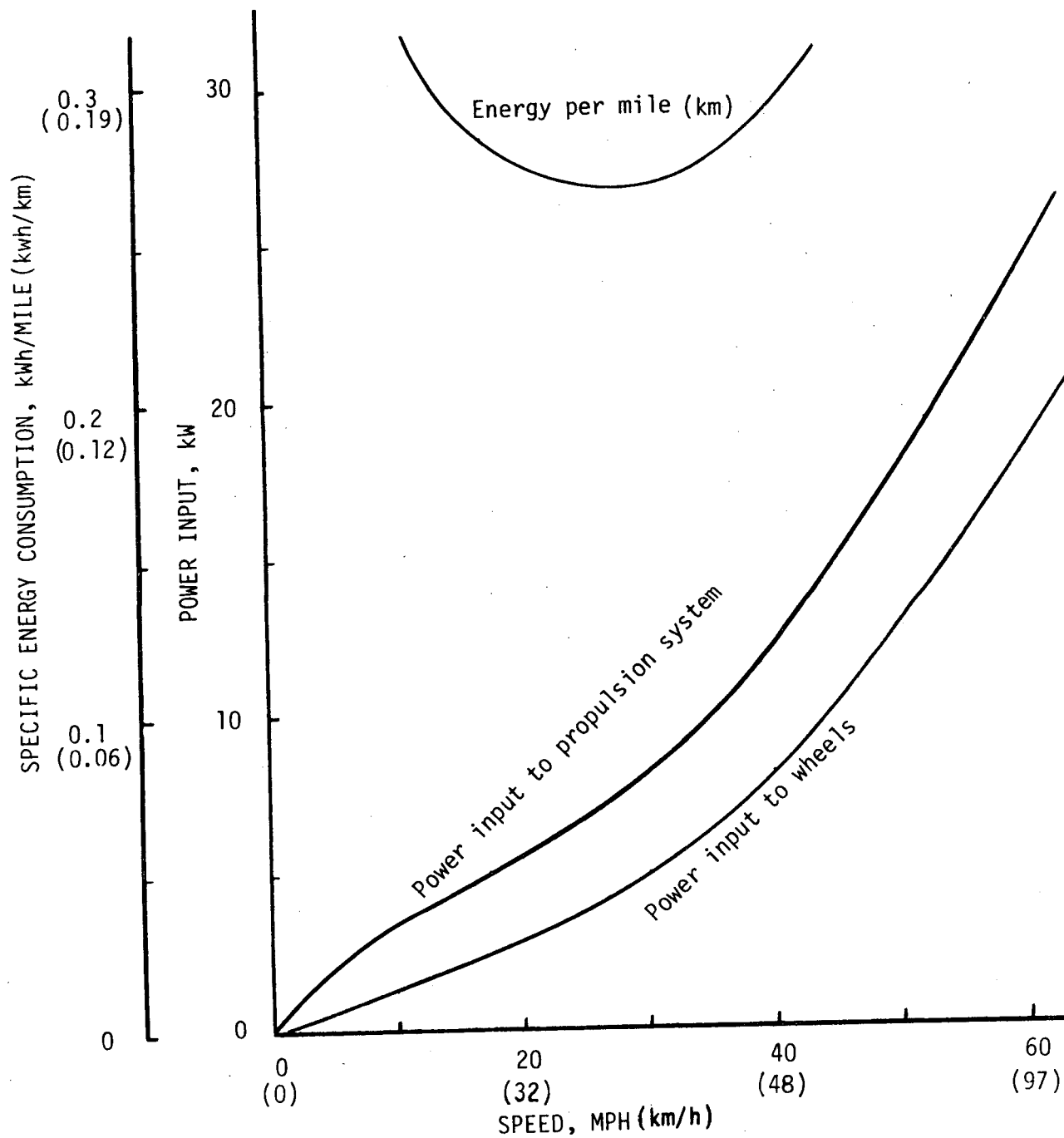


Fig. 4.27. Power and energy vs speed for a DMET electric vehicle. (XBL 774-777)

5. Impact Analyses

Many of the impacts of the DMET system will be similar to those of battery-powered vehicles. Environmental impacts can be expected to differ only in degree. The effects on institutions such as electric utilities and government funding agencies are less closely related. The economic impact on the consumer, and the effects on highway departments will also involve different considerations.

For those areas of similarity, Refs. 7 and 8 provide a basis for comparison with other vehicles and transportation technologies. In addition, Ref. 8 provides a spectrum of detail regarding the impacts of electric vehicles in the Los Angeles area. The following analyses use the above references extensively to extrapolate data relative to ICE automobiles and battery-powered vehicles for estimating the impact of DMET coupled/battery-powered hybrid vehicles.

Impacts that are considered in those references and are also briefly treated here include:

- 5.1. ECONOMICS
 - 5.1.1. Operating Costs
 - 5.1.2. Transportation Supplies and Services
- 5.2. ENERGY CONSUMPTION
- 5.3. RESOURCE CONSUMPTION
- 5.4. ENVIRONMENTAL EFFECTS
- 5.5. INSTITUTIONAL EFFECTS

When DMET systems are adapted to automatic vehicle controls, additional impacts will occur:

- 5.6.2. Accident Rates
- 5.6.3. Traffic Capacity
- 5.6.4. Energy Management

5.1. ECONOMICS

The economic implications of the use of electric vehicles have been studied by numerous investigators. The two studies previously mentioned are particularly useful in providing data for economic comparisons with battery-powered conventional automobiles. The DOT report⁷ provides detailed cost data for vehicles, some of which are directly related to the EPA report.⁸ In the economic analyses

that follow, attempts are made to achieve as much consistency in estimating methods as possible in order that comparisons are drawn equitably.

Two economic analyses are presented. One presents operating costs of automobiles, partitioned as "capital insensitive costs" and "capital sensitive" costs, allocated on a per-vehicle-mile basis. This analysis allows comparison between conventional and electric automobile technologies.

A second analysis briefly reviews the commercial economic impacts of electric vehicles on "transportation supplies and services" as discussed in the references in order to identify new considerations injected by the DMET technology.

5.1.1. Operating Costs

A DMET vehicle characterization was made that is as similar in payload and performance to the ICE vehicle and lead-acid battery-powered four-passenger automobile characterizations in Refs. 7 and 8 as possible. While the characterizations are consistent with respect to proportions and are useful on a comparative basis, they should not be regarded as representative of a 1980 automobile, either ICE or electric. The current trend in the weight of production cars is sharply downward, and any electric vehicle would be designed with even more attention to weight control.

Table 5.1 presents a characterization of the major components of the DMET and the battery-powered vehicles. The smaller battery in the DMET vehicle allows the use of a lighter chassis, and smaller motor and controller. These weight savings are partially offset by the power pickup that the DMET vehicle carries.

Table 5.2 shows the relative production and retail costs of the ICE and battery-powered vehicles and the DMET vehicle. The DMET vehicle is estimated to cost \$900 more than the ICE vehicle and \$600 less than the battery-powered vehicle. The major cost reductions in the DMET vehicle as compared to the battery vehicle are attributable to its lighter weight. The saving in the required battery capacity more than offsets the weight of the power pickup.

Table 5.1. Characterization of Major Electric Vehicle Components.

Component	DMET Vehicle		Lead-Acid Battery Powered Vehicle	
	Weight , lb (kg)	Description	Weight , lb (kg)	Description
Vehicle without power	1550 (704)	Chassis, body, suspension, and power train	1625 (738)	Chassis, body, suspension, and power train
Battery	500 (227)	Lead-acid, for short range on streets	1500 (681)	Lead-acid battery for 55-mile range
Motor	242 (110)	dc traction, 63 hp (47 kW)	315 (143)	dc traction, 82 horsepower
Motor controller	63 (29)	Solid state "chopper"	85 (38)	Solid state "chopper"
Power pickup and suspension	265 (120)	20 kW nominal	---	
66 Coupled power control	20 (9)	Solid state		
Curb weight	<u>2640</u> (<u>1199</u>)		<u>3525</u> (<u>1600</u>)	

Table 5.2. Estimated Production and Retail Costs of 4-Passenger Automobiles.

	Electric Automobiles		
	Battery-Only*	DMET	ICE Auto*
<u>Production Costs</u>			
Body, chassis, suspension (~0.9 \$/lb, or \$2/kg)	\$ 1490	\$ 1420	
Motor (~1.2 \$/lb, or \$2.6/kg)	375	290	
Electrical System			
Motor controller (~1.1 \$/A)	225	175	
Coupled power control and rect.		100	
Power pickup and suspension		210	
Energy Storage			
Lead-acid battery (~0.42 \$/lb, or \$0.93/kg)	630	210	
Total Production Cost	\$ 2720	\$ 2405	\$ 1955
Retail Price (~2 × production cost)	5400	4800	3900
*From Ref. 7.			

Table 5.3 is a cost estimate, per lane mile, for a DMET power system as described in this report. The estimate shows that the cost of the power conditioner is approximately 40% of the total cost. It may become feasible at some future date to obtain power for the system directly from utilities at the frequency required (~180 Hz). The resulting reduction in cost would be a major fraction of the power conditioner cost. The cost estimate assumes the use of an existing freeway lane on which the power source is installed, and the availability of space at roadside for power conditioners. Included is the cost of repaving the lane, and the cost of power distribution to the power conditioner from a modest distance.

From the power-system cost estimate can be derived an estimate of the allocation of this capital cost per DMET vehicle. This estimate utilizes the following data:

- 11,000 vehicle-miles per day per lane-mile of urban freeway as determined from California Department of Transportation statistics.
- 40% of DMET vehicle-miles are traveled on the power system, as is characteristic of conventional cars.
- 29 vehicle-miles per day are ascribed to each DMET vehicle as in typical urban areas.

$$\frac{\text{roadway power system cost}}{\text{vehicle}} = \frac{348,800 \times 29 \times 0.4}{11,000} \frac{\$/\text{lane-mile} \times \text{miles}}{\text{vehicles/lane}} = 368 \$/\text{vehicle}$$

If this were financed by bonds and amortized at 5% through a motor vehicle tax in 20 years, the cost to the vehicle owner would approximate 29.5 \$/year.

In the study of electric vehicle impacts in the Los Angeles region, it was assumed that the vehicle's battery charging energy was supplied in off-peak hours, so that no additional power generating capacity was required. Part of the energy supplied to the DMET system is provided as it is being used. This load will add to the normal peak load of the utility system and may require the construction of additional generating plant capacity.

Table 5.3. Cost Estimate for the Roadway Power System.

<u>Power Source</u>	<u>Material</u>	<u>k\$/Lane Mile</u>
Core	Laminated silicon sheet steel	99.0
Conductor	Stranded aluminum	21.3
Insulation	Board, sheet, and elastomer	23.9
Fasteners	Studs in concrete	7.0
Installation		20.0
Subtotal		<u>171.2</u>
<u>Power Conditioner</u>		
	5 MW/unit, enclosed and installed per lane mile	138.0
<u>Road Work</u>		
Preparation and traffic control		15.0
Resurfacing		24.6
		<u>39.6</u>
		<u>348.8 k\$/Lane-Mile</u>
		<u><u>(216.8k\$/lane-km)</u></u>

Figure 5.1 shows the effect of the added DMET load, based on data developed in Ref. 8 for the Los Angeles area in 1990 and using the "upper bound" penetration of 73% for electric vehicles. The DMET load per vehicle used is 20 kW. This includes the propulsion load of the vehicle plus a battery-charging load as the vehicle travels on powered roadways. Forty-two percent of the total traffic is assumed to be on freeways as was projected for 1990. The added peak load for the area is 1.43×10^6 kW, which, if allocated to each of 6.7 million vehicles, would represent approximately 0.21 kW per vehicle. The capital cost of 1.43×10^6 kW of generating plant capacity at $324 \text{ \$/kW}^9$ would be 463 M\$, or 69 \$ per DMET vehicle. If this were financed with 5% bonds and amortized in 20 years through a motor vehicle tax, the cost to the vehicle owner would approximate 5.5 \$/year.

The sum of the vehicle taxes for amortizing the roadway power system and the extra generating capacity is thus $(29.5 + 5.5) \text{ \$/year}$, or 0.0035 \$/vehicle mile at 10,000 vehicle miles per year. The estimates indicate that the capital requirements for system construction are of minor concern when taken in perspective with other components of vehicle operating costs.

Table 5.4 shows the comparative costs of supplying 0.39 kWh per mile to an electric vehicle with batteries or a DMET power system. Although the initial cost per kWh of daily use of the DMET power system is from 0.8 to 2.0 times the initial investment in batteries, over a lifespan of 20 years the batteries cost from 5 to 15 times more than the DMET system in procurement costs alone.

Table 5.5 summarizes operating cost estimates for the three vehicles. Most of data for the ICE and battery automobiles were taken directly from Ref. 7. One adjustment to that data was made for this tabulation. In the reference from which the data were derived, a lead-acid battery efficiency of 46% had been assumed. This was adjusted to 65%, including battery-charger losses, in order to achieve a closer correlation with the demonstrated performance of several electric vehicles. The adjustment resulted in a lower energy cost (by a fraction of a cent per mile).

Table 5.4. Relative Cost of Supplying Energy to Electric Vehicles from Batteries and from a DMET System

	Batteries*					
	Present Lead Acid	Improved Lead Acid	Ni-Zn	-Cl	Na-S	DMET
Initial cost/kWh	\$40	\$45	\$100	\$60	\$50	\$81 ^a
Lifetime cost/kWh	\$0.10	\$0.056	\$0.10	\$0.17	\$0.10	\$0.01 ^c
20-year cost/lane mile ^b	3.1×10^6	1.8×10^6	3.1×10^6	5.3×10^6	3.1×10^6	0.35×10^6
20-year cost/lane km	1.9×10^6	1.1×10^6	1.9×10^6	3.3×10^6	1.9×10^6	0.22×10^6

a
$$\text{DMET cost/kWh} = \frac{348.8 \text{ k\$/LM}}{11,000 \frac{\text{VM}}{\text{LM day}} \times 0.39 \frac{\text{kWh}}{\text{VM}}} = 81 \frac{\$}{\text{Nominal Daily kWh}}$$

b $11,000 \frac{\text{VM}}{\text{Lane mile day}} \cdot \frac{0.39 \text{ kWh}}{\text{VM}}$, excludes cost of maintenance and power losses.

c
$$\frac{348.8 \text{ k\$/LM}}{11,000 \frac{\text{VM}}{\text{LM day}} \times 365 \frac{\text{D}}{\text{Y}} \times 20\text{Y} \times 0.39 \frac{\text{kWh}}{\text{VM}}} = 0.01 \frac{\$}{\text{kWh}}$$

*Source: F. J. Port, "Energy Sources," Electr. Vehicle News, 11/76.

Table 5.5. Operating Cost Estimates for 4-Passenger Mass-Produced Vehicles
 [Costs in Cents per Vehicle Mile (cents per vehicle km)]

<u>Capital Insensitive Costs</u>	ICE Auto*	Electric Automobiles	
		Battery-Only*	DMET
Energy cost	1.87	1.77	1.23
Oil	0.18	--	--
Repairs and Maintenance	1.95	1.09	1.09
Tires and accessories	0.40	0.43	0.40
Pollution device and maintenance	0.86	--	--
Insurance	1.53	1.53	1.53
Garage, parking, tolls	1.96	1.96	1.96
Subtotal--C.I. Costs	<u>8.75</u>	<u>6.78</u>	<u>6.21</u>
<u>Capital Sensitive Costs</u>	(5.44)	(4.21)	(3.86)
Depreciation, base vehicle	3.91	3.49	3.66
Roadway power system amortization	--	--	0.35
Depreciation, battery	--	4.20	0.84
Finance costs (@ 5% compounded)			
Vehicle	2.42	2.77	2.90
Battery	--	0.66	0.22
Taxes--Fees (@ 3% of acquisition cost/year)	1.17	1.63	1.44
Subtotal--C.S. Costs	<u>7.50</u>	<u>12.75</u>	<u>9.42</u>
Total Operating Cost	<u>16.25</u>	<u>19.53</u>	<u>15.63</u>

* From Ref. 7.

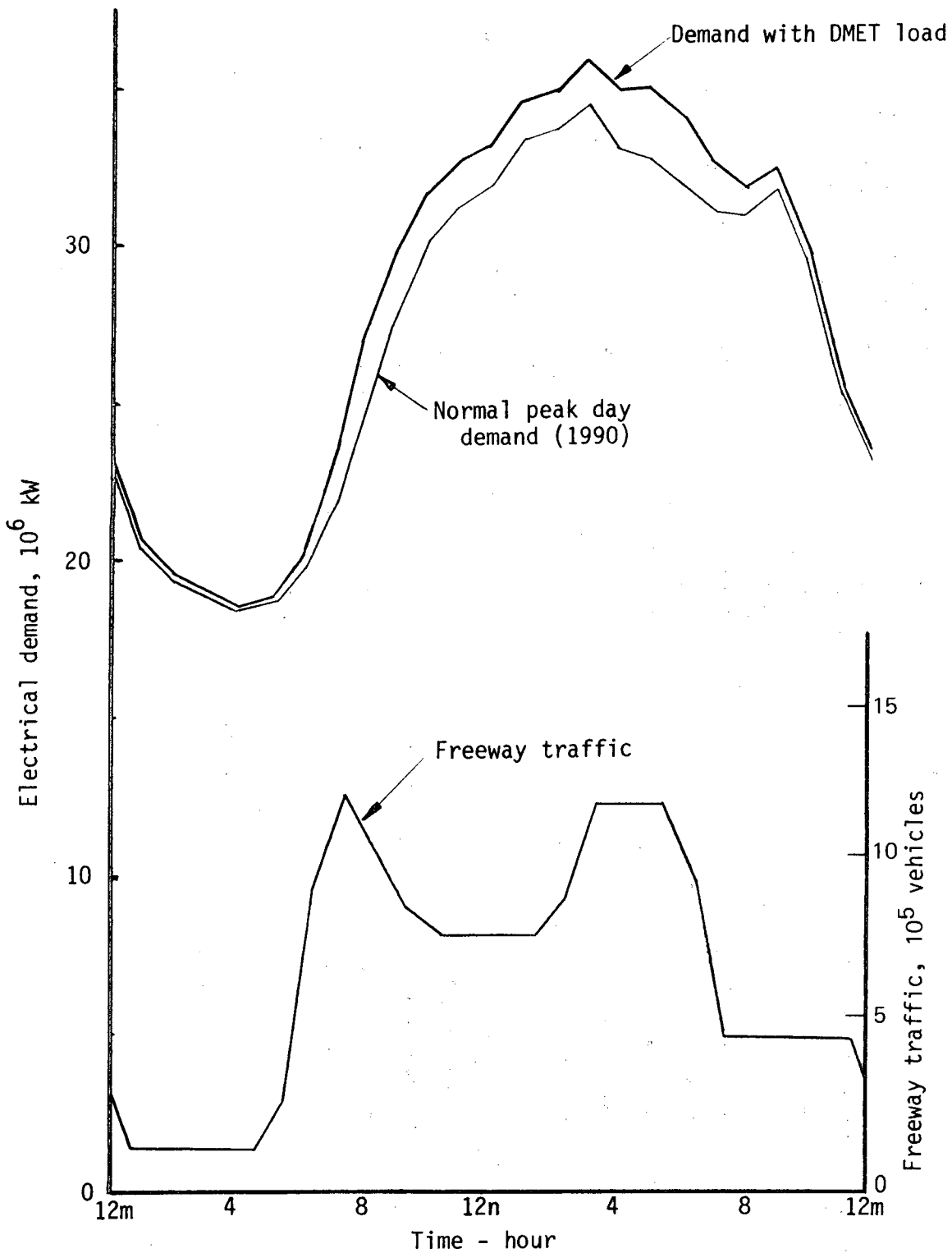


Fig. 5.1. Electrical demand and freeway traffic vs time for the Los Angeles area in 1990. (XBL 774-778)

The table shows that the "capital insensitive costs" are significantly less for both electric vehicles than for the ICE auto. Battery depreciation costs of 4.2 cents/mile (2.6 cents/km) cause the total operating cost of the battery-powered vehicle to be the highest of the three.

The DMET vehicle's operating cost benefits greatly from the availability of the roadway power system. Its battery is much smaller and is used for only 60% of the miles traveled. The analysis assumed equal battery life for both electric vehicles; this may favor the battery-powered vehicle, since the battery discharge cycles in the DMET application will be typically much shallower than is the case for the other vehicle.

The data for the ICE vehicle in the table were based on a fuel economy of 21.4 mpg (9.1 km/l). The estimated operating cost for this vehicle exceeds that of the DMET vehicle by 0.6 cent per mile (0.4 cent/km).

5.1.2. Transportation Supplies and Services

Reference 8 identified the battery manufacturing and petroleum distribution industries as those most likely to sustain major impacts from the use of electric vehicles in the Los Angeles area.

The estimated increase in employment in battery manufacturing, which was projected for the Los Angeles area in 1990, ranged from 6571 (zinc chlorine battery) to 69,728 ("worst" lead acid battery). This estimate was based upon a 100% changeover to electric cars. The impact of the DMET system would be less because of the smaller battery packs required. Similar rates of implementation of DMET vehicles would result in 2/3 less increase in employment (employment being directly related to the weight of batteries produced).

The decrease in employment in the petroleum distribution industry was projected to be over 30,000 jobs in 1990. This projection would not be significantly altered by the implementation of DMET systems, although the smaller battery packs used in the DMET vehicles could be expected to decrease even further the small amount of effort devoted to battery maintenance.

The decrease in employment in 1990 in the "automotive aftermarket" (i.e., automotive parts suppliers) and auto repair industries was projected to be over 20,000 jobs. The major effect was due to the

displacement of the high maintenance requirements of the ICE vehicles. The impact from the DMET system's implementation could be expected to be similar.

The DMET system brings into play four new sources of employment:

1. Manufacture of electrical equipment for the roadway power system.
2. Installation of roadway power systems.
3. Maintenance of roadway power systems.
4. Increased production of power.

It was projected in Ref. 8 that 196 million vehicle miles per day would be traveled in the Los Angeles area in 1990, and that 42% would be on freeways. Assuming (1) a continuing average daily traffic of about 11,000 vehicles per lane for these urban freeways and (2) an "upper bound" DMET vehicle implementation of 73%, a total of 5463 lane-miles of freeway power system would be installed.

A more likely projection would be a reduced number of lane-miles of system as a result of the evolution of automatic highway controls. The addition of automatic vehicle controls would decrease the required number of lane miles by more than half. For the purposes of this analysis, it is assumed that the total costs involved would be similar.

Table 5.6 summarizes the estimated magnitude of the additional employment due to the implementation of the DMET system. If the construction of the 5463 lane miles was accomplished in 16 years, the average yearly construction effort would supply 2838 jobs. Maintenance and power production would provide 1598 jobs on a continuing basis.

5.2. ENERGY CONSUMPTION

The energy requirements for electric vehicles of various weights operating in the SAE "metropolitan" driving cycle were estimated in Ref. 8. The data from that reference for vehicles with lead-acid batteries are plotted in Fig. 5.2. Using the estimated DMET vehicle curb weight of 2640 lb plus an average passenger load of 1.56×150 lb (consistent with average vehicle occupancies as determined from the 1974 Transportation Report), the estimated net energy consumption is 0.28 kWh per vehicle mile. This energy is provided at different efficiencies during battery operation and coupled power operation:

Table 5.6. Estimate of Employment in the Los Angeles Region Due to the Installation of 5463 Lane Miles of DMET System

<u>Manufacturing</u>	<u>Basis for Estimate</u>	<u>Employment</u>
Item (1)	25% of total manufacturing cost of roadway system components (250 k\$/lane-mile) spent locally at 20,000 \$/manufacturing man year.	17,072 man years
<u>Construction</u>		
Item (2)	35% of 463 M\$ power generating plant cost spent for local labor at 25,000 \$/man year.	6,482 man years
Item (3)	100% of roadway and power conditioner installation work (100 k\$/lane-mile) from local labor at 25,000 \$/man-year.	21,852 man years
	Subtotal roadway power system manufacturing and construction	45,406 man years
<u>Maintenance</u>		
Item (4)	One $\frac{\text{man year}}{\text{year}}$ required for each four lane miles.	1,366 $\frac{\text{man years}}{\text{year}}$
<u>Increased Production of Power</u>		
Item (5)	0.162 employee/MW, ^a 1430 MW DMET addition	232 $\frac{\text{man years}}{\text{year}}$
		1,598 $\frac{\text{man years}}{\text{year}}$
^a "19th Stream Station Cost Survey" Electrical World, Nov. 15, 1975.		

Battery (58% of miles traveled):

$$0.28 \text{ kWh/mile at 65\% battery efficiency} \times 0.58 = 0.250$$

Coupled power operation (42% of miles traveled):

$$0.28 \text{ kWh/mile at 85\% power system efficiency} \times 0.42 = 0.138$$

$$\text{Average energy input, kWh/mile(kWh/km)} \quad \underline{0.388} \quad (0.241)$$

Figure 5.3 shows the equivalent energy savings in barrels per day relative to ICE automobiles of various fuel economies. The figure is based upon a DMET vehicle use of 73% of the 196×10^6 VM/day in 1990 in the Los Angeles region.

5.3. RESOURCE CONSUMPTION

In the study of the impact of electric vehicles in the Los Angeles region, the major impacts on material resources identified were those relating to battery materials. In the case of the lead-acid battery, these were lead and antimony. The impacts were found to be most severe in the early years of implementation of electric vehicles. The ability to recycle the materials moderates the projected impact once the inventory of batteries is established. A 17% national usage of electric vehicles was shown to require 33% of the normal demand for lead and 43% of the normal demand for antimony in 1980. The use of DMET systems could reduce the consumption of those materials by more than half.

The DMET power systems will utilize large amounts of capacitors, transformers, insulation materials, aluminum and steel. It was shown in a preceding section that approximately 5463 lane miles of system would be required to meet "upper bound" usage requirements in 1990 in the Los Angeles region. An estimate of the major materials necessary for constructing this system network in 16 years is shown in Table 5.7, together with the percentage of 1974 national demand which the material quantities represent.

The consumption of capacitors would represent 12.6% of the 1972 production rate; this is a rate of considerable importance to that industry. The requirements were estimated from the date for the unoptimized design study. Requirements for optimized designs may be significantly different. The consumption of transformers would represent about 0.6% of 1974 demand and would represent a minor consideration in the market place.

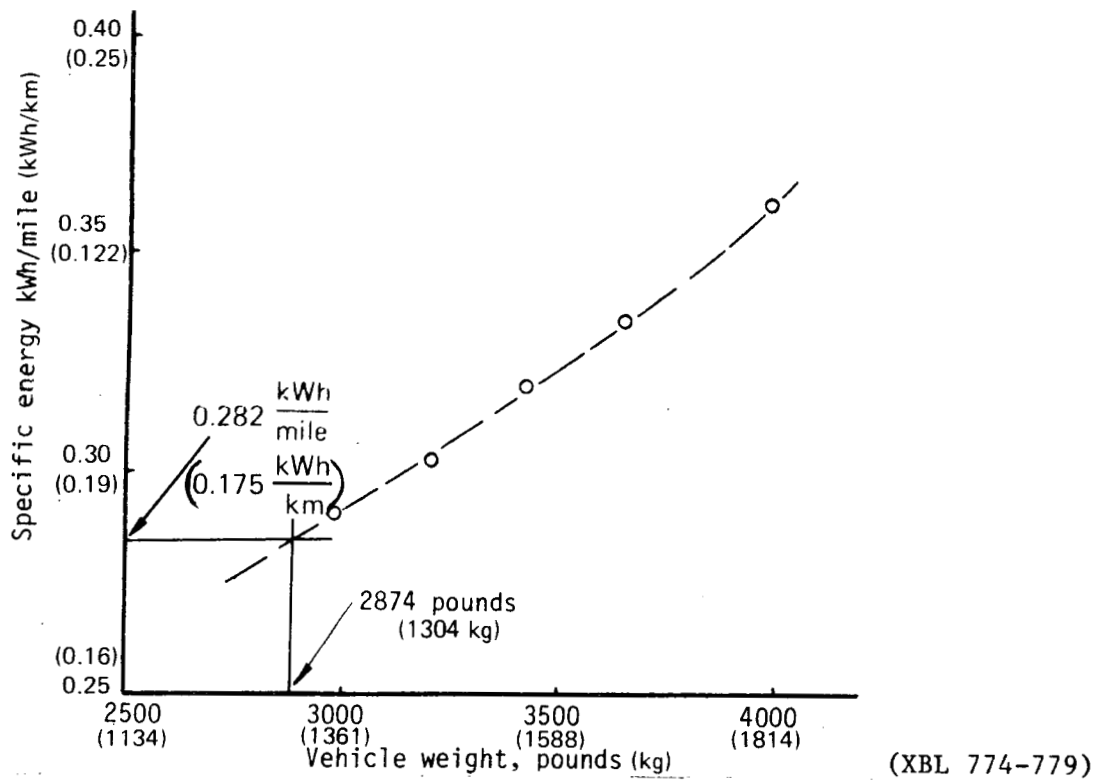


Fig. 5.2. Specific energy consumption vs vehicle weight. (Source: "Impact of future use of electric vehicles in the Los Angeles region," EPA 460/3-74-020-b, General Research Corporation.)

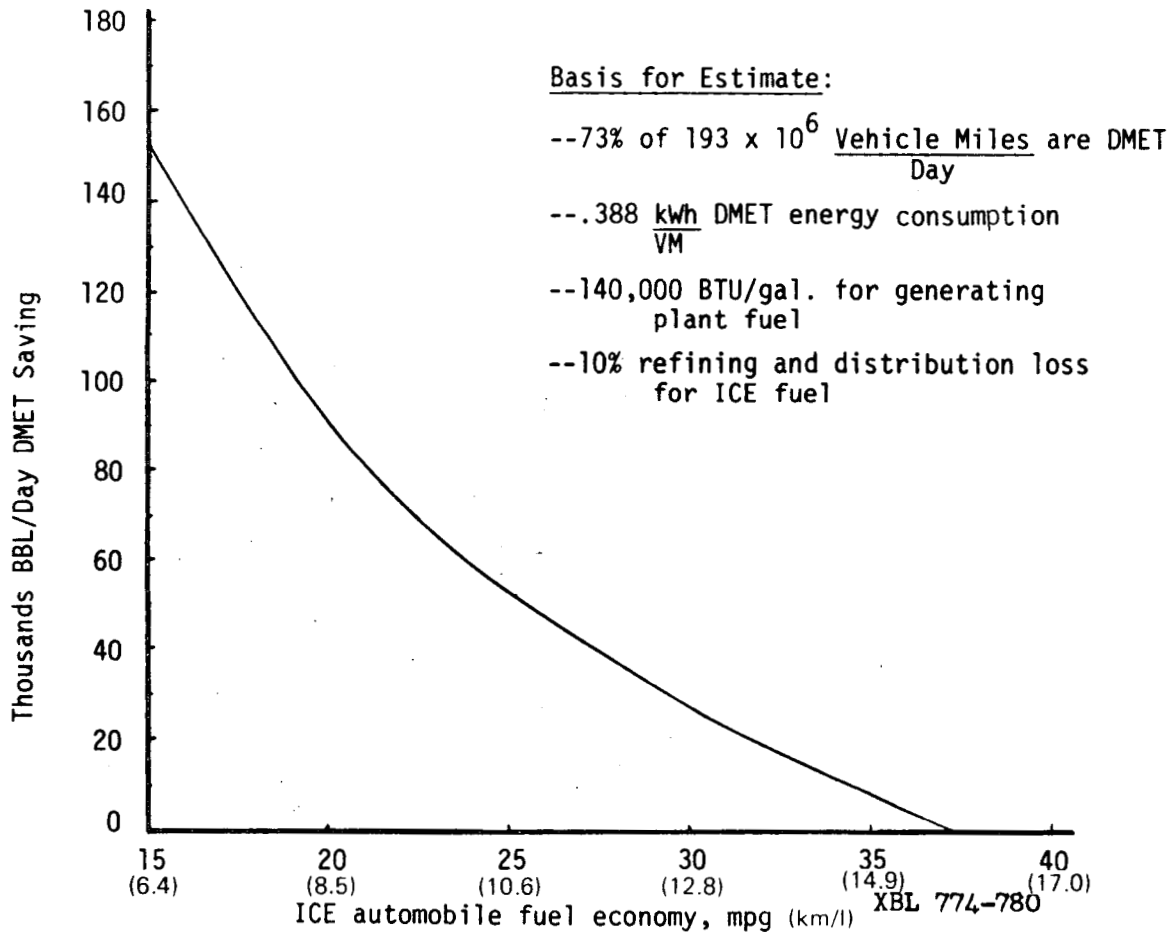


Fig. 5.3. DMET petroleum saving in the Los Angeles area vs fuel economy of displaced ICE automobiles. (XBL 774-780)

Table 5.7. Estimate of Material Requirements for Constructing DMET Systems

Item	Material	Unit Requirement	Los Angeles Consumption	% 1974 Demand	National Consumption	% 1974 Demand
<u>Source</u>						
Core	Steel	37.5 lb/ft	33,800 tons/year	0.03 ^a	660,000 tons/year	0.6
Conductor	Aluminum	4 in. ²	8.7×10 ⁶ lb/year	0.08 ^b	169.0×10 ⁶ lb/year	1.6
Insulation	Elastomer	5 in. ²	1449 long tons/year	0.04 ^c	28,286 long tons/year	0.8
<u>Power Condition and Vehicles</u>						
Transformers	Primarily steel	3000 kVA/lane mile (9 \$/kVA)	9.2 M\$/year	0.06 ^d	180 M\$/year	12
Capacitors	Aluminum	2389 kVAR/lane mile	10.6×10 ⁶ kVAR/year	12.6 ^e	2.06×10 ⁸ kVAR/year	245
	Plastic	38 kVAR/vehicle				
<u>Bases for Estimates:</u>						
Los Angeles region: 5,463 lane miles constructed in 16 years.						
National: 200,000 lane miles constructed in 30 years.						
1974 demand data from Statistical Abstract of U. S., 1975, Department of Commerce:						
^a "Steel mill products apparent supply," 1974 = 119,609,000 tons.						
^b "Aluminum mill products," 1974 = 10,442×10 ⁶ lb.						
^c "Synthetic rubber distribution," estimate from 1973 data, 1974 = 3.60×10 ⁶ long tons.						
^d "Transformer shipmates," estimate from 1972 data, 1974 = 1.5×10 ⁹ \$.						
^e Capacitor shipments, data from Department of Commerce, 1972, 112.5 M\$ "other than electronic" plus 454 M\$ "electronic" = 566.5 M\$; estimate 1974 ≈ 1972.						

The consumption of aluminum would be more than 4,000 tons per year but would represent less than 0.1% of the 1974 national demand.

These material requirements can be roughly extrapolated to a national projection. The population of the Los Angeles region was 9.7 million in 1970. The national population in standard metropolitan statistical areas in 1970 was 148.3 million. Using the ratio 148.3:9.7 to project the demand for materials due to DMET system urban installations, and allowing for the interstate highway system, a total of 200,000 lane miles (322,000 lane km) might be required. Spreading the demand for a national construction program over 30 years instead of 16 as in the Los Angeles region provides the national demand estimates shown in Table 5.7. Of the materials, the estimated demand for capacitors at 245% of the 1972 rate would require a large increase in manufacturing capacity, although the associated material requirements, primarily aluminum and plastic, do not appear to be of major significance. The 12% demand increase for transformers does not appear to be a major consideration.

The successful development of automatic highway/vehicle controls for the DMET system could reduce the number of lane miles by a large factor. The total system lane miles and resources required would be reduced proportionally, but the rate of construction and resource use might not be affected during the shorter construction program.

5.4. ENVIRONMENTAL EFFECTS

The effects on pollution levels in the Los Angeles area of an 80% changeover to electric cars in 1990 were explored in Ref. 8. The analysis concluded that ozone, NO₂, CO, and particulate pollution were beneficially affected by a modest amount. Sulfur dioxide pollution, however, increased by 7% as a result of the increased load on power generating plants.

Two differences between the characteristics of the electric vehicles used for the Los Angeles study and the DMET vehicles can be expected to influence projections of pollution levels. One difference is the time at which pollutants are generated during the day. The DMET system provides approximately two-thirds of the vehicles' energy in real time, that is, predominantly in the hours from 6 a.m. to 6 p.m. This difference could be expected to be disadvantageous in that industrial pollutant emissions are also highest in those hours.

The second difference, which is significant to air quality projections, is the reduced energy requirements of the DMET system as compared to electric vehicles that rely solely on stored energy. The energy efficiency of batteries is lower than that achievable with a DMET power system, and a battery-powered vehicle capable of practical range in metropolitan driving must carry a large, heavy battery pack. The combination of these effects results in an energy economy improvement of approximately 30% with the DMET system. The average reduction in pollutant emissions due to electric vehicles could be expected to also approximate 30%, compared to lead-acid battery-powered vehicles. The reduction would be less in the event that an advanced battery development program is able to provide batteries of improved energy density and efficiency.

5.5. INSTITUTIONAL EFFECTS

5.5.1. Highway Departments

Highway departments will be responsible for many planning functions such as route and lane selection and probably power conditioner locations. They will also contract and administer construction programs.

Figure 5.4 shows the rate at which the freeways system in the U. S. was constructed. Thirty-eight thousand, seven hundred and fifty-six miles of freeways were constructed between 1956 and 1974. The 1974 National Transportation Report (DOT) projects that 977.4×10^9 vehicle miles will be traveled in all urbanized areas in 1989. If this traffic were all DMET, the required number of urban lane-miles would approximate 100,000,* roughly equivalent to 17,000 miles of six-lane freeway construction. The urban construction program would thus be approximately half of the magnitude of the freeway construction program from 1956 to 1974. The addition of interstate routes may add a similar amount of construction.

Maintenance requirements of the power system will be a logical function of state highway departments. Part of the staffing may parallel the structures of "Power and Way" departments of rapid transit systems that maintain the "third rail" and associated electrical substations. This is a function that does not presently exist in typical highway departments. The maintenance of the roadway power source itself will

* Assumptions: 42% of travel on DMET freeways; 11,000 vehicles per lane-day.

involve work that should be compatible with the skills of typical highway maintenance personnel. Maintenance requirements of the source will be largely mechanical in nature and will probably involve such operations as surface repairs and positional (elevation) adjustments of the roadway source.

The task of billing of power to the highway power system user may fall to highway departments, or to the electric utility that supplies the power. In either event, existing vehicle registration systems can provide the basic data system. Meters on vehicles can monitor the energy coupled from roadway systems. Periodic meter reading can be accomplished at designated locations, or could be done automatically by transponders in powered roadways.

5.5.2. Electric Utilities

5.5.2.1. Added Peak Load. The effect of added DMET loadings on the demand curve of a typical electric utility system was shown in Fig. 5.1. The increase in annual peak load in that example (for Los Angeles) was 4%. This increase would occur over a period somewhat longer than the construction period (see Section 7).

Peak loads in the utility industry were 75% of "capability" in the summer of 1975.¹⁰ The capability of the industry increased at an average rate of 8%, or 30 million kW annually from 1968 through 1974. Assuming that the projections for the nation are similar to those of the Los Angeles area, the industry may be able to accommodate the introduction of DMET systems with a modest perturbation to its growth plans.

It was estimated in a previous section that the average increase in peak load per DMET vehicle was approximately 0.21 kW. A national population of 100 million DMET vehicles would represent an increased peak load of the order of 21 million kW, which, if accommodated in a 30-year construction program, would require an added annual increment of less than 0.2% to the average growth rate of 8%.

5.5.2.2. Power Distribution. A survey of the locations at which power would be available to a network of freeway power systems was acquired from the Pacific Gas and Electric Company for the San Francisco Bay Area. The locations are shown in Fig. 5.5. Data from the Los Angeles basin indicate an even more extensive distribution system. The Los Angeles freeways would be served by the Los Angeles Department of Water and Power, and the Southern California Edison Company. The data indicate that freeways typically are proximate to heavy electrical distribution facilities. The spacing of the facilities is generally compatible with the desired spacing of DMET power conditioners.

5.6. THE TRANSPORTATION SYSTEM

5.6.1. Public Transit

The DMET power system could become the basis for the extensive use of buses on freeways and improved bus service within cities. Urban buses are the least capital intensive of public transit facilities and provide the major share of public transit passenger miles. One of their major shortcomings is their low average speed, which may be one reason for their being the least preferred form of transit.¹¹

"Freeway flyers" have demonstrated their ability to attract significant public ridership. These buses travel on freeways and are provided with loading/unloading facilities beside the freeway. The DMET technology could be of considerable significance to such systems in three possible ways.

a) The electric DMET buses would be more quiet and would not have the pungent odors that diesel buses emit. The public could be expected to accept their presence on feeder routes through residential areas where they would not accept diesel buses.

b) The electric DMET buses could incorporate electronic fare collection in conjunction with automatic operation of multiple doors. Such techniques could aid in increasing the average speed of buses.

c) The addition of automatic traffic controls to DMET systems could provide a route priority for buses, particularly on street arterials, which would also increase the average speed.

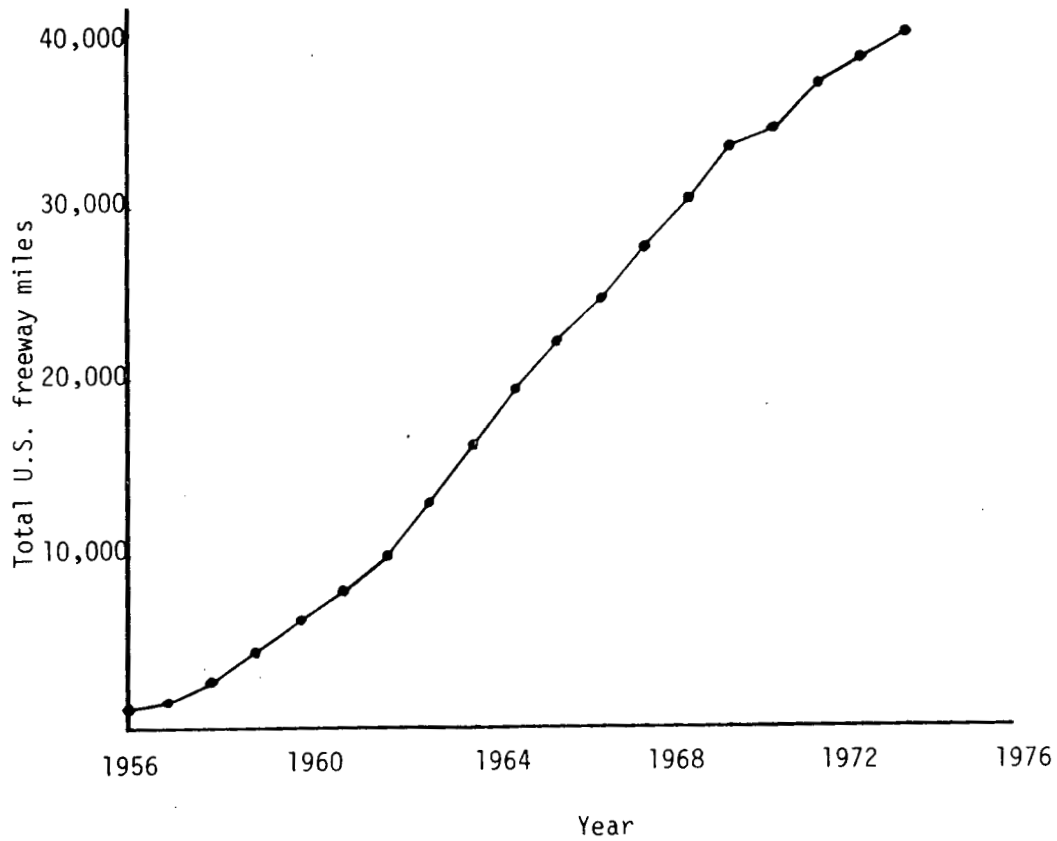


Fig. 5.4. Freeway constructed from 1956 through 1974. (Source: Highway Statistics, Department of Transportation). (XBL 774-781)

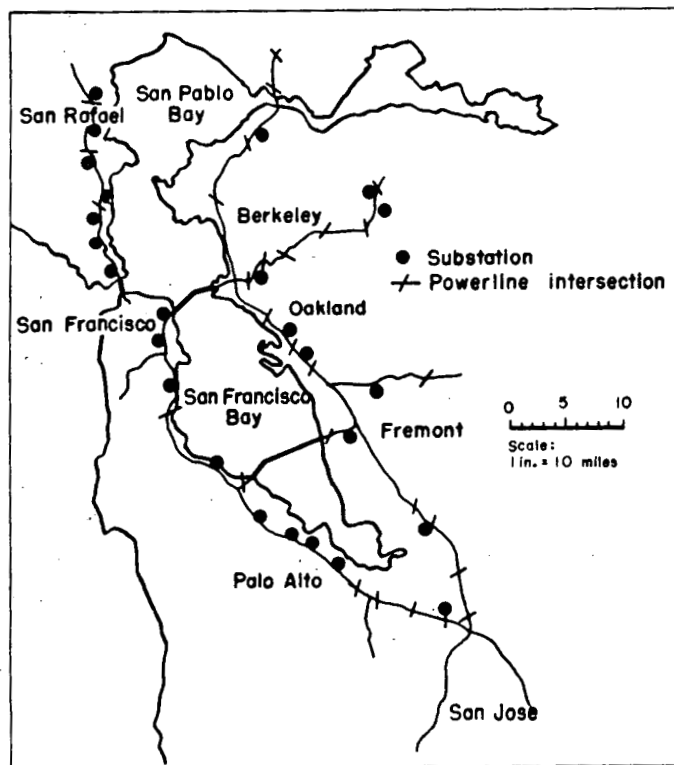


Fig. 5.5. Roadway power system in the San Francisco Bay Area showing locations of available electric power. (XBL 774-782)

5.6.2. Accident Rates

A study was made of another dual mode concept, Ref. 12, in which vehicles are constrained and automatically controlled on a guideway for part of their operating cycle. This study estimated that guideway portions of trips exhibited accident rates with characteristics similar to rail, bus, and airline systems.

In the DMET concept, operational modes will initially be similar to those of conventional automobiles, although improved guidance is provided to vehicles by the presence of the roadway power system, and DMET vehicles have an incentive to remain in the powered lane without passing. These effects may provide a reduction in accident rates, although such projections are speculative at this time. When the systems are expanded to include well-developed, fail-safe automatic vehicle controls, large reductions in accident rates are possible.

5.6.3. Traffic Capacity

The public has demonstrated a reluctance to support the continued construction of freeways in urban areas, even though existing freeways generally are supersaturated with traffic during commuting hours. Without a breakthrough in the development of a new mass transit technology, the only feasible way to keep pace with increasing traffic loads is to increase the capacity of existing urban freeways. The most likely way to accomplish this is to add automatic traffic and vehicle controls.

The traffic capacity of automated highways has been estimated by investigators of several system concepts. A factor of two increase in capacity would be considered to be conservative by most of the investigators. Existing roads provide maximum passenger-carrying capacity with vehicles traveling at approximately 40 miles per hour (64 km/h) with spacings of 100 ft (30 m). Doubling this capacity with an automatic control system would require relatively modest improvements, e.g., 50 miles per hour (80 km/h) and vehicle spacings of 63 ft (19 m).

The DMET system provides inherent capabilities that are useful to automatic control systems.

1. Vehicle guidance is readily obtained by tracking the magnetic field of the roadway power source.

2. The gaps between evenly spaced sections of the power source's core are useful in deriving velocity and distance inputs from the roadway (with magnetic sensors).

3. Vehicle occupancies are electronically detectable from the change in magnetic characteristics of coupled sections of source core.

4. Vehicle "following moves" can be safely regulated by trailing prohibitive signals in the power source behind moving vehicles. The signals can be coupled through the power pickup of following vehicles to initiate a deceleration and thus maintain a safe spacing.

5.6.4. Energy Management

The energy that DMET vehicles draw from roadways can be metered on the vehicles, much as household energy is. The reading of the meter could be accomplished by any of several means, e.g.:

1. Periodic meter reading at authorized facilities.
2. Automatic meter reading with a transponder installed in roadway.
3. Periodic reading by customer, using a standardized postcard reporting system.

Vehicle registrations provide an existing data base for identifying vehicles and for monitoring their energy consumption. Output from such a data system could provide information of considerable use to energy and traffic planners. The data system would also be useful in the event that the necessity arose to ration or allocate energy in some equitable manner.

6. Comparisons of Alternate Non-Petroleum-Based Automobile Technologies

Options for maintaining the public's mobility in the coming decades will continue to be centered on the automobile. In order to retain its viability, the automobile must adapt to new energy sources. Major options in automobile power systems include:

- a) Hybrid systems
 - Coupled electric power and battery/electric drive
 guideway--direct contact^{*}
 freeway--inductive coupling (DMET)^{*}
 - Heat engine and battery/mechanical and electric drives
 - Heat engine and flywheel/mechanical and electric drives
- b) Stored energy power systems such as:
 - Battery/electric drive^{*}
 - Flywheel/electric drive, or flywheel/mechanical drive
 - Thermal storage and heat engine/mechanical drive
- c) Internal combustion engines that use synthetic fuels^{*} or hydrogen.

The following comparisons are necessarily conjectural to a considerable degree, since most of the options are immature technologies. The prospect of widespread use of hydrogen-powered cars is not treated here, since the probability associated with the use of synthetic fuels is much stronger.¹³ Hybrid vehicles other than the dual-mode hybrids are also not treated, as they are generally considered to be of only temporary viability (i.e., they would be supplanted by the successful development of an advanced battery or other less-complex electrical power system).

6.1. DMET

6.1.1. Risks

This technology can be considered to be a low-to-moderate development risk. The design of the power system involves only well-understood physical phenomena. Risks are largely those associated with the development of cost-effective hardware designs and possible unforeseen operational effects.

* Selected for assessment as most promising technologies.

6.1.2. Public Receptivity

The receptivity of the public to the DMET system will be influenced by:

- The extent of the available DMET roadway power system network.
- The public's reaction to electric vehicle power systems.
Effects such as limited off-system range and speed, quieter and cleaner automobiles, and reduced operating costs are involved.
- Gasoline availability.
- Expected improvements in safety and in traffic flow.

6.1.3. Infrastructure

The new infrastructure required will include organizations and/or equipment for:

- Roadway power-system maintenance and operation. This structure would probably be added to existing state highway departments.
- Power billing. This structure could be either added to state highway departments or to electric utilities.
- Battery and electric vehicle power system maintenance. This could be incorporated into existing automotive service facilities.
- Increased production of capacitors.
- Light-duty battery charging in residential garages. These could be packaged "plug-in" units.
- Manufacture and installation of roadway power systems. This would fall within the expanded capability of the heavy electrical equipment manufacturing industry.

6.1.4. Economics

The capital investment required for DMET systems to accommodate the bulk of the 2.5×10^{12} "local" passenger miles projected by DOT for the year 1990 would be of the order of a hundred billion dollars (approximately \$437 per vehicle served). This level of investment is roughly a third of the size of the investment projected by the DOT for the expansion of the auto mode from 1976 to 1990.¹⁴ It was shown in this report that the investment in DMET power systems would be returned to the public through savings in vehicle operating costs. (Each mil saved on the average cost-per-vehicle-mile represents an annual

national saving of a billion dollars.) Operating costs in the DMET Vehicle were estimated to be 15.6¢/vehicle mile (9.7¢/vehicle km).

The power requirement for battery-charging facilities in the typical user's garage could be provided by the existing electrical service. The small battery pack on the vehicle would store approximately 6.5 kWh of energy. The cost of a charger for a battery of this size would approximate \$420 (see Fig. 6.1).

Thus the total capital investment per DMET vehicle for the roadway power system and charging facilities is \$857.

6.1.5. Energy

It was shown elsewhere in this report that a small DMET vehicle is capable of achieving energy economies equivalent to 34 miles per gallon (14.5 km/l) of gasoline in metropolitan driving cycles. The efficiency of the system results from the combination of the high efficiencies of the power generating plants and roadway power coupling system.

6.1.6. Other Costs and Benefits

No significant commercial or residential dislocations would be caused by the implementation of the DMET system, assuming increased route capacity through incrementally added automatic control systems.

Employment in the distribution of petroleum products would be reduced and would be only partially offset by new jobs in power system construction and maintenance.

Atmospheric and noise pollution would be significantly reduced by the replacement of the automobile heat engines with electric power systems.

Traffic flow and safety could be significantly improved with the adoption of some elements of automatic control (guidance, lane access, or headway).

The transportation service supplied by a DMET automotive system would be distributed among the population much the same as is that of present automobiles. The inclusion of freeway DMET buses by legislative fiat could, however, provide a large expansion of public transit to metropolitan areas.

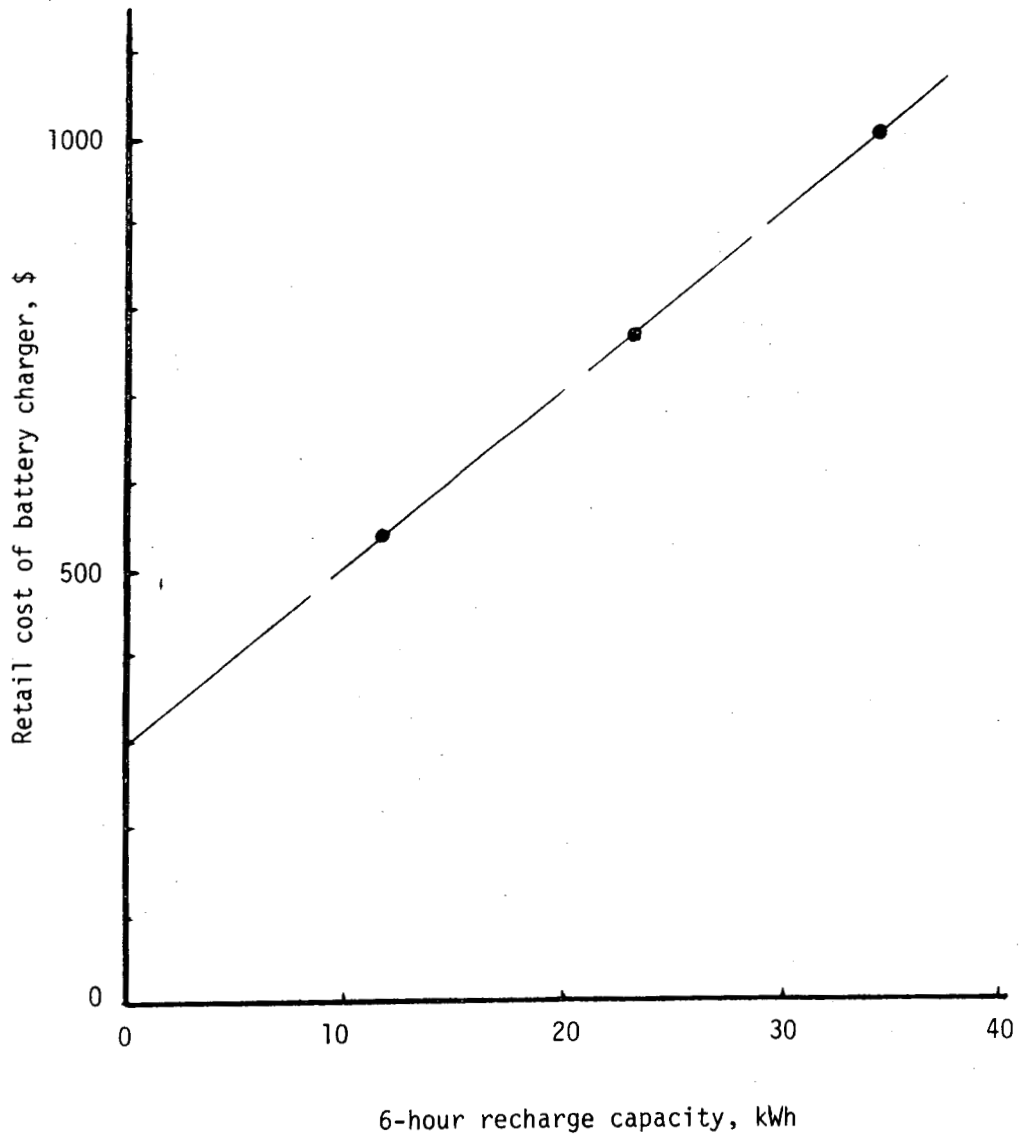


Fig. 6.1. Retail cost vs recharge capacity of commercial battery chargers.
(Source: McCormick-Morgan Co., San Francisco.) (XBL 774-783)

6.2. GUIDEWAY DUAL-MODE SYSTEMS

This technology is summarized in Ref. 12. A special guideway network is constructed on which vehicles operate in an automatically controlled mode. The vehicles could be either ICE powered cars, small electric cars, or buses especially designed for the system, or powered "pallets" onto which conventional vehicles could be driven for transport on the guideway. In the "New Small Vehicle concept," small cars or buses could operate off the guideway on stored energy for short-range, low-speed travel. Propulsion power on the guideway would be transferred to the small cars or buses by direct contact with continuous guideway conductors. This technology is not directly comparable to the DMET concept since its primary purpose is to provide extremely high passenger-carrying capacity line-haul corridors through the use of advanced automated control systems, while the DMET system is intended for area wide and national networks with automatic controls as an optional addition. The "dual modes" are considered to be automatic operation and manual vehicle operation in the guideway concept, while DMET "dual modes" are considered to be operation on either coupled power or on stored energy.

6.2.1. Risks

The guideway technology is generically related to operating automated guideway systems such as the "Airtrans" system at the Dallas-Fort Worth airport or the "ACT" system near Detroit. Remaining technical risks probably lie mostly in the ability to design vehicles, control systems, and guideways that could safely interface with the occasionally low level of operating skills of the general public.

6.2.2. Public Receptivity

The receptivity of the public would be influenced by:

- The extent of the guideway network.
- The reliability of the system and its vehicles.
- The limited utility of the system, i.e., the efficacy of the system is limited to serving a high-density community adjacent to a major central business district.
- Increased operating costs.

- Gasoline availability.
- Expected improvements from the system with regard to safety, noise, and traffic flow.
- Dislocations caused by guideway construction in urban areas.

6.2.3. Infrastructure

New infrastructure required will include organizations and/or equipment for:

- Guideway power system maintenance and operation. This structure could be added to existing highway departments.
- Usage billing. This could also become a function of existing highway departments.
- Battery and electric-vehicle power-system maintenance. This would be accomplished by, or on contract to the public agency that owned and operated electric vehicles. In the case of privately owned vehicles, service facilities could be incorporated into existing auto service facilities.
- Manufacture and installation of guideway systems. This would fall within the capability of rapid rail transit construction contractors.

6.2.4. Economics

The levels of capital investment projected¹² for dual-mode systems in the Boston area are shown in Table 6.1, together with the derived capital costs and the operating cost per equivalent vehicle (equivalent to the 1.6 passenger miles per mile of the average duty of an urban automobile). The "equivalent" values allow a direct comparison with those of the alternate technologies.

Since the operating costs are higher than those of other vehicles by from 3 to 7 cents per vehicle mile, the directly perceived costs are highly unfavorable. The reference study indicated a significant positive total benefit balance, but most positive components were indirect savings such as the value of shortened trip time, land value increase, and tax revenue increase.

Table 6.1.

System	Capital Cost M\$ ^a	Daily Trips	Capital Cost per ^b Equivalent Vehicle	Equivalent Operating Cost ^c per Vehicle Mile (km), ¢
Small vehicle	4,200	1.58×10^6	3,300	22.4 (13.9)
Pallet plus bus	2,630	1.31×10^6	2,500	21.4 (13.3)
Automated highway	1,620	1.17×10^6	1,700	21.3 (13.2)

^aExclusive of vehicles.

^bAssumes two daily trips per user, 1.6 users per vehicle.

^cEquivalent operating cost is the cost of 1.6 passenger miles, equivalent to the average loading of an urban automobile (for use in comparing to other technologies).

The cost of battery-charging facilities for electric vehicles could be expected to be similar to those for DMET vehicles, i.e., 420 \$/vehicle.

6.2.5. Energy

The referenced dual-mode study indicated a near equivalence in energy use for the small vehicle and pallet systems when compared to the 1990 plan for conventional transportation modes. The small electric vehicle option could, however, achieve energy savings similar to those of the DMET system.

The energy loss mechanisms for the DMET and guideway systems are generally similar. Power supply losses will consist mostly of transformer losses. Roadway losses in the guideway system will be mostly resistive losses in conductors and contact losses.

A reduced energy consumption (approximately 40%) was projected for the automated highway vehicle system that used ICE automobiles. This was projected because of the elimination of stop-and-go driving and traffic congestion.

6.2.6. Other Costs and Benefits

Approximately 20 households and 20 businesses per route mile would be displaced by guideway construction.

Atmospheric pollution would not be significantly affected, but noise pollution was projected to be greatly reduced.

Traffic flow, trip times, and safety were projected to be very much improved by the system in the areas served by the dual-mode network.

The transportation service supplied by the system would be distributed among the population with greatest benefits to minority and low-income groups.

6.3. BATTERY-POWERED VEHICLES

6.3.1. Risks

The efficacy of battery-powered vehicles will depend almost entirely on the successful development of improved batteries. Present lead-acid batteries are useful only for limited-range, limited-performance vehicles. Adequate electric vehicle technology (other than the battery) exists for the production of first-generation vehicles.

6.3.2. Public Receptivity

The receptivity of the public to battery-powered vehicles will depend on:

- Range and performance capability. This in turn will be dependent on the degree of success of battery development programs.
- First cost. Battery costs are a major component of the purchase price. The cost of the energy storage subsystem ensures that the vehicle's cost will be significantly higher than other vehicles of comparable payload.
- The public's reaction to cleaner, quieter electric power systems.
- Gasoline availability.
- The safety and maintenance requirements of the energy storage subsystem. Advanced batteries may operate at high temperatures and contain hazardous materials.

6.3.3. Infrastructure

New infrastructure required will include organizations or equipment for:

- Battery and electric-vehicle maintenance. This could be incorporated in existing automotive service facilities.
- Heavy-duty charging facilities in residences. A vehicle capable of a maximum range of 50 miles (80 km) would require a residential electrical service of approximately 25 A at 220 V and a large battery charger.
- Heavier utility power distribution network. The increased residential power services would require a corresponding increase in distribution system facilities, since battery-charging loads would occur concurrently throughout an area.

6.3.4. Economics

The capital cost associated with heavy charging facilities includes the charging equipment and the extra distribution system capacity. Figure 6.1 shows the trend of costs for battery chargers. A vehicle capable of 50-mile range would require battery capacity of approximately 25 kWh. The estimate of the total costs for a typical residential charger installation would include \$825 for the charger and \$225 for

the 220-V convenience outlet (assuming that 220-V service exists in the garage's electrical panel) for a total of \$1,050.

An increase in distribution transformer capacity for the peak (initial) charging rate of 25 kW would cost \$225 (at \$9/kVA) for equipment. Allowing \$100 for installation costs results in a total added distribution cost of \$325. Thus the capital cost per vehicle for charging facilities totals \$1,375.

Operating costs for battery-powered vehicles were estimated in this report to be 19.5 ¢/vehicle mile (12.1¢/vehicle km).

6.3.5. Energy

The electric vehicle with a lead-acid battery is estimated to provide an energy economy equivalent to 24 miles per gallon (10.2 km/ℓ).

6.3.6. Other Costs and Benefits

The battery-powered car would not improve traffic flow. The dislocations due to freeway construction would occur in the same number as would be the case with the continued use of the ICE automobile.

Employment in the distribution of petroleum products would be reduced. Atmospheric and noise pollution would be significantly reduced. No improvement in the distribution of transportation services and costs among the population could be expected.

6.4. INTERNAL COMBUSTION ENGINE AUTOMOBILES USING SYNTHETIC FUELS

These vehicles would be small vehicles of advanced design, i.e., of lightweight construction and including extensive emission controls. The fuel, derived from coal or oil shale, would substitute directly for gasoline and distillates. Methanol fueled engines are not considered in this analysis because of their apparent cost and infrastructure disadvantages.

6.4.1. Risks

Risks with respect to fuel availability are generally confined to the as-yet unproved costs and efficiencies of the fuel-manufacturing processes. Risks associated with the vehicles would be centered, as they now are, on the technological advances that are required to meet fuel economy and emission standards.

6.4.2. Public Receptivity

The changes in receptivity that might be anticipated would result from:

- Increased fuel costs. Data for the cost of the numerous synthetic liquid fuels are generally speculative, often because of the difficulty of predicting inflation effects and because pilot plants of significant scale have not been built. It is clear, however, that these fuels will be much more expensive than those derived from petroleum.
- Traffic congestion. A transportation system that continues to rely on ICE automobiles will require the construction of many new lane miles of arterial roads. It is unlikely that the public will support enough new construction to keep the pace with even the present level of congestion.
- Changes in vehicle design. Fuel economy and emission standards may force the ICE auto to become a vehicle of performance and comfort that is inferior to existing cars.

6.4.3. Infrastructure

The major addition will be the new manufacturing and transportation facilities required for the synthetic fuels.

6.4.4. Economics

The capital required for the production of synthetic fuels--by several processes--was estimated in Ref. 13. When allocated to an automobile that achieves 23 miles per gallon and drives 10^4 miles per year (i.e., uses 0.028 barrel of fuel per day), these costs range from 190 to 370 dollars of capital investment per vehicle.

Operating costs would approximate 19¢/vehicle mile (12¢/vehicle km), assuming a 1 \$/gallon fuel price.

6.4.5. Energy

The fuel economy of these vehicles could be expected to match that of petroleum-fueled cars. The DOT projections indicate a fleet average economy of 26 mpg in 1990. This relates to a comparative fuel economy of 23 mpg (9.8 km/l) when 10% refining and distribution energy losses are included.

Large amounts of energy would be consumed in the manufacture of synthetic fuels. The net energy ratio, which is the ratio of energy available in the product to the energy expended or lost in production processes, was estimated in Ref. 13 to range from 0.6 to 1.6.

6.4.6. Other Costs and Benefits

The manufacture of synthetic fuels at nationally significant rates would result in the construction of a large number of facilities, many located in areas that are presently sparsely populated. Reference 13 cites many adverse environmental effects that would result.

Large amounts of capital would be diverted to establishing the industry. Synthetic fuel production under the "maximum credible implementation" rate, would provide just over half of the gap between domestic fuel supplies and demand by the year 2000.

Many resources in addition to coal and shale would be diverted to the industry's use. The consumption of water was shown to be particularly troublesome.

Atmospheric and noise pollution from vehicles would remain the same as with the use of petroleum fuels, as would traffic flow, safety, and the quality of the transportation service.

6.5. SUMMARY OF COMPARISONS

Comparisons between the chosen automobile technologies are summarized in Table 6.2. The risks associated with the technologies are compared as to "developmental" risks and "implementational" risks. The risks range from low in the case of synthetic fueled ICE technology to the moderate to high risk associated with battery development for electric autos. The DMET system ranks as a low to moderate risk.

All the technologies require added infrastructure. When these additions are rationalized to a "per-vehicle" basis, the capital costs for added infrastructure range from 260-440 dollars for synthetic-fuel systems to 2100-3700 dollars for the guideway dual-mode system. The DMET cost, \$860, ranks second to the synthetic-fuel system.

The energy use of the automobile ranges from a low of 23 mpg for the ICE automobile to 34 mpg for the DMET vehicle. The fuel consumption of the ICE auto is derived from the 26 mpg projection from Ref. 14 less a 10% penalty for refining losses. The value used for guideway dual-mode vehicles is the same as for the ICE auto as suggested in Ref. 12.

Table 6.2. Comparison of Alternate Non-Petroleum Based Automobile Technologies.

Technology	Risks/ Quality	Major Added Infrastructure	Infrastructure Capital (\$/Vehicle)	Vehicle Energy [Equiv. MPG (km/l)]	Vehicle Operating [Cost \$/VM (Vkm)]	Other Costs, Benefits Environ.-Transport.-Socioecon.		
<u>Freeway Dual Mode (DMET)</u>	Develop./L ^a Impl./M	Roadway power System Small battery charger	860	34 (14.5)	0.16 (0.10)	F ^b	O-F	O-F
<u>Guideway Dual Mode</u>	Develop./L Impl./M	Guideway Guideway power system	2100-3700	23 ^c (9.8)	0.21 (0.13)	O	F	F
<u>Battery-Powered Electric</u>	Develop./M-H Impl./M	Heavy battery charging facilities	1,450	24 (10.2)	0.20 (0.12)	F	O	O
<u>Synthetic-Fuel ICE</u>	Develop./L Impl./L	Syn. fuel manufacture and transport	260-440	23 (9.8)	0.19 (0.12)	U	O	O

^aL = low, M = moderate, H = high.

^bF = favorable impact, O = small impact, U = unfavorable impact.

^cGuideway systems credited with equivalence to ICE; see Ref. 12.

Equivalent vehicle-operating-cost estimates range from a low of 0.16 \$/VM (0.10 \$/Vkm) for the DMET system to a high of 0.21 \$/VM (0.13\$/Vkm) for the guideway dual-mode system.

Other costs and benefits are diverse. The synthetic-fuel technology is environmentally obnoxious, while the battery-powered and DMET vehicles are relatively benign. Transportation service improvements are available in the guideway dual-mode system and possibly in the DMET system (depending on the degree of automation). Beneficial socio-economic impacts could be delivered by the guideway dual-mode system (i.e., improved service to the poor and "disadvantaged" social sectors) and possibly by the DMET system, depending on the degree of public transit incorporated into the system.

7. Implementation Sequence

The implementation of the DMET system in a metropolitan area will involve several phases. The initial phase will begin once the development of system hardware has been advanced to production designs. This will have required a program that included the construction of several iterations of engineering and production prototypes of the roadway power system and DMET vehicles.

The initial phase would consist of the planning and construction of a pilot system. The primary objective of this phase would be to acquire operational, maintenance, and traffic and energy management experience. A secondary objective would be to demonstrate the system's value to the public. The pilot system might utilize a radial route between the central business district and a residential area. A hypothetical example in the Los Angeles area is shown in Fig. 7.1. The figure illustrates the area that would be served by a DMET power system consisting of about 25 route miles (50 lane miles). Although this short pilot system would be useful only for commuting and shopping, the route chosen is heavily traveled (approximately 164,000 average daily traffic). The acquisition of DMET vehicles by a very small fraction of the route users would create a cost-effective load for the power system.

A fortunate characteristic of the DMET power system is its compatibility with existing ICE vehicles. It will not be necessary to prohibit the use of the DMET lane by other vehicles until the lane approaches saturation loading with DMET traffic.

Achieving a level of use of the DMET pilot system that would provide adequate statistical data relative to traffic flow and vehicle usage patterns would require a rapid buildup of DMET vehicle population. Public participation could be encouraged through several options or combinations of options such as:

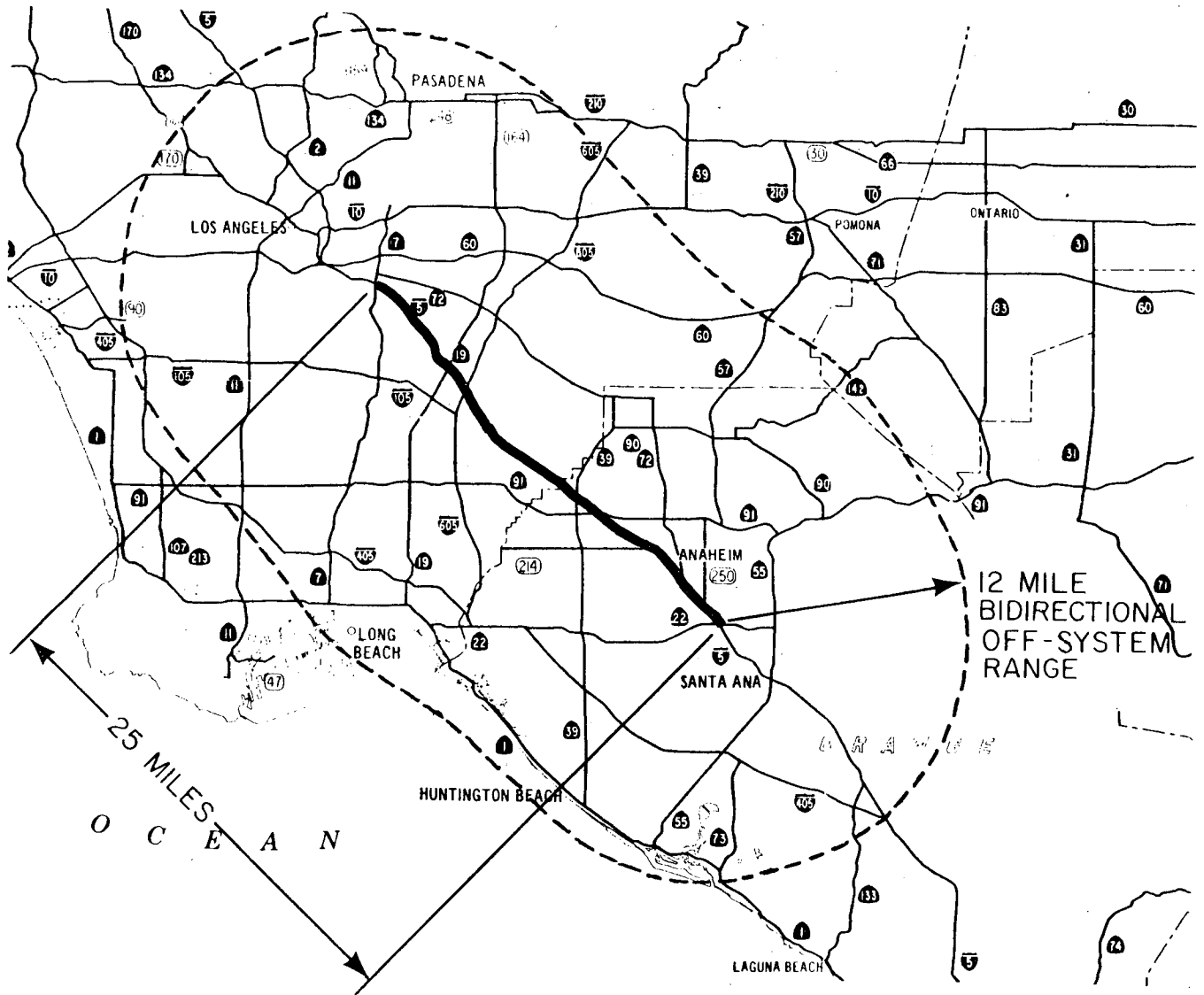


Fig. 7.1. Range envelope for a 25 mile (40 km) route DMET pilot system in Los Angeles. (XBL 774-784)

1) Providing free electrical energy from the roadway power system. For the average user this would represent a daily saving of about half a dollar.

2) Partially subsidizing the purchase price of the vehicle. The use of this option would surmount the problem of vehicle purchase prices that could initially be higher than would be the case at high vehicle production rates.

3) Reserving the powered lanes for use by DMET vehicles only. This option probably is the least desirable, since it could be expected to induce some antagonism to the DMET system by degrading traffic flow for conventional vehicles.

The rate at which the public will adopt the DMET system will be speculative until the pilot installation is made. Several factors can be expected to play a major role in determining the rate:

1) The availability and cost of gasoline.

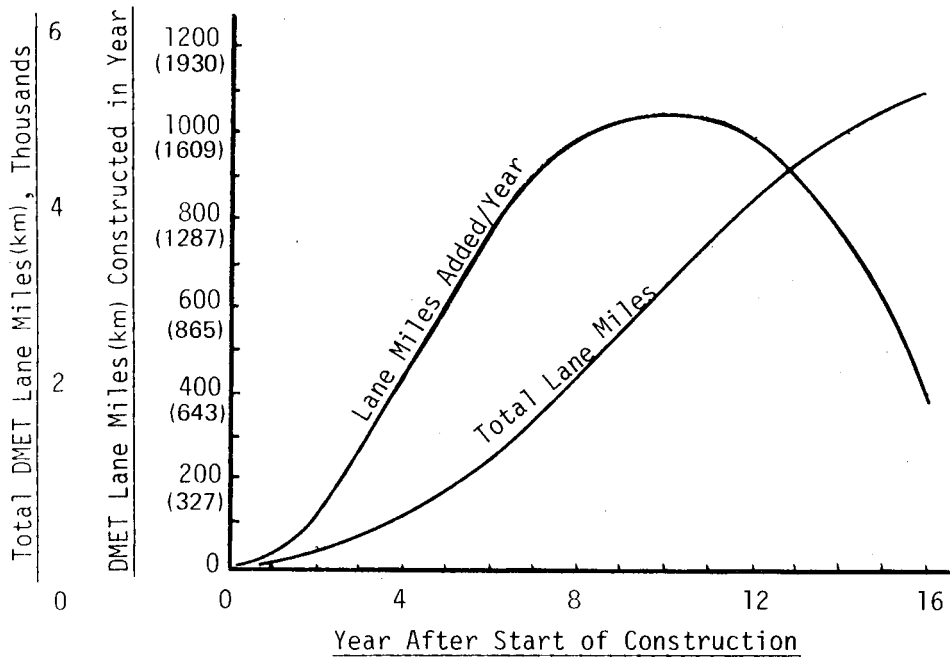
2) The cost of ICE vehicles with advanced emission controls vs the cost of DMET vehicles.

3) The public's reaction to the utility and performance of DMET vehicles.

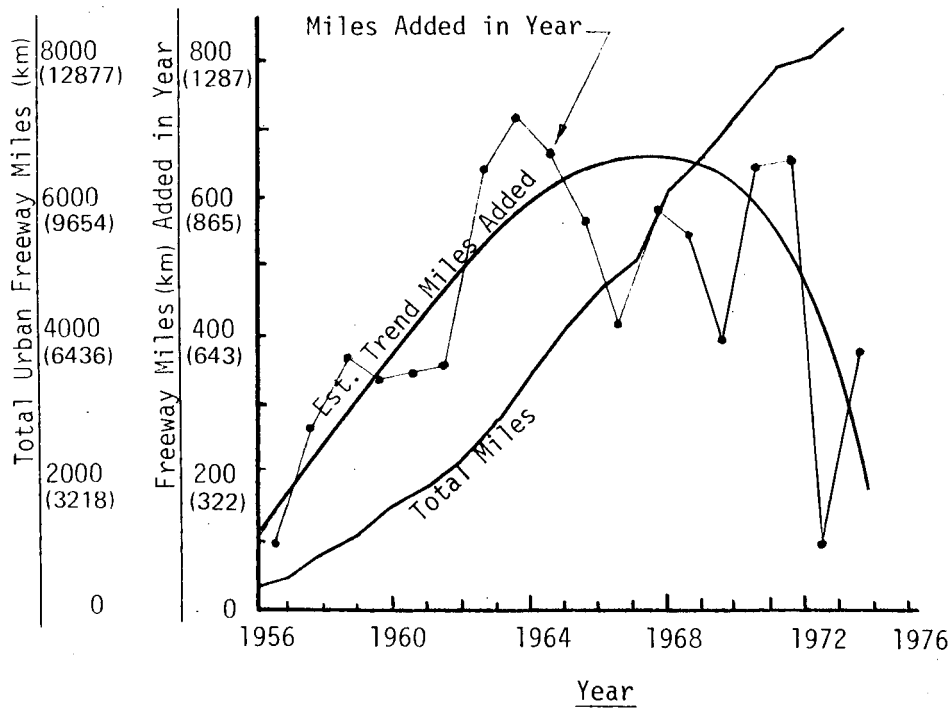
4) The availability of funding for construction of DMET roadway power system.

The DMET system might be best expanded by emphasizing the early construction of paired lanes (one in each direction) on each major freeway. The area-wide mobility thus created would remove any range limitation from the DMET vehicles and stimulate their acceptance. Extra lanes on major routes could be added as DMET vehicle populations grew.

A postulated implementation sequence has been developed for the Los Angeles region, using the historical pattern of the freeway construction program as a model. Figure 7.2 shows the similarity between the hypothetical construction rate and the actual freeway construction program. The 16-year DMET construction program chosen for the Los Angeles area is similar to the freeway program. A program significantly shorter (or longer) could be accommodated, since the construction program does not involve the dislocation of residences and businesses as did the freeway program.



a) DMET ESTIMATED CONSTRUCTION PROGRAM



b) URBAN FREEWAY CONSTRUCTION PROGRAM

Fig. 7.2. Similarity between hypothetical construction rate of DMET lanes and the actual freeway construction program. (XBL 774-785)

An assumed rate of DMET vehicle population growth on a new DMET route is shown in Fig. 7.3. The 7-year build-up period was chosen to generally match the typical new-car acquisition period of the consumer. This relationship was used to derive the area-wide increase in vehicle population shown in Fig. 7.4. The capital committed to system construction was derived from Figs. 7.2 and 7.3 and is shown in Fig. 7.5.

The finished network would include the routes shown in Fig. 7.6. The development of an automatic highway and vehicle control system could be expected to chronologically parallel the construction program. The plans for network expansion would be influenced by the progress of that work. It was estimated elsewhere in this report that 5463 DMET lane-miles would be required to support 73% of the Los Angeles traffic in 1990. This assumed a continuation of the 11,000 vehicle per lane day average daily traffic that is now characteristic of California urban freeways. The successful development of an automatic highway control system of modest capability would readily double the traffic capacity of the powered lanes. The result would be to reduce the needed power system construction by nearly half. It is interesting to note that the additional traffic load capability of an automated lane would come nearly "for free" as far as the roadway power system is concerned. This is because extra loading is accommodated primarily by voltage/current phase changes in the power system rather than requiring an increased voltage or current capability. The implementation cost and schedule for the DMET construction program due to the addition of automatic controls would not be reduced in direct proportion to the reduction in lane miles. The automatic control system could be expected to add costs and construction time of roughly the same magnitude as for the lane miles of power systems that it displaced.

Extra power generating capacity might have to be constructed for the added vehicle load during this phase (the increase in the utility peak load was estimated to be 4%). The cost of this increased capacity is included in the capital costs, which are shown in Fig. 7.6.

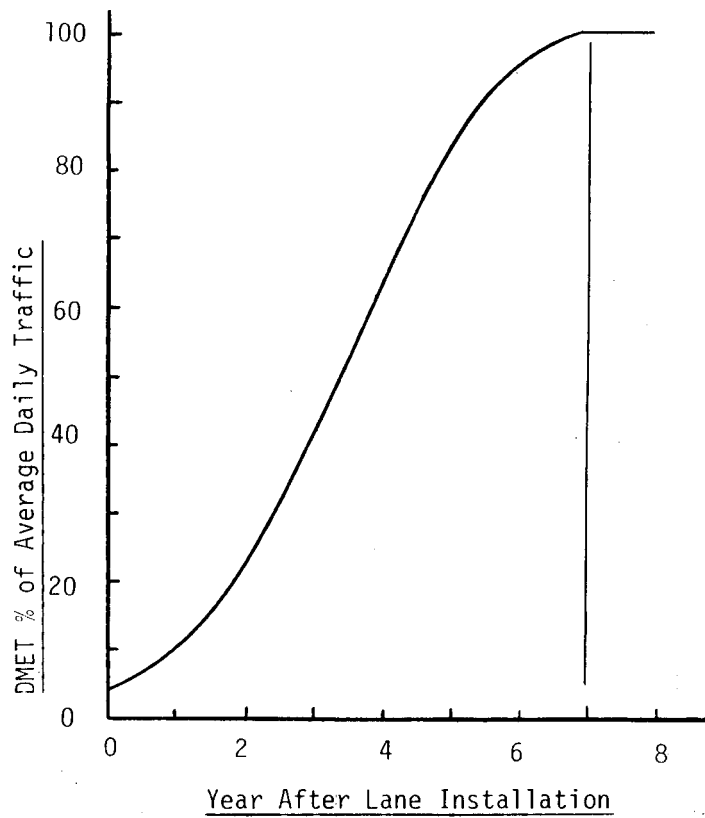


Fig. 7.3. Percent DMET vehicle traffic vs time after lane construction. (XBL 774-786)

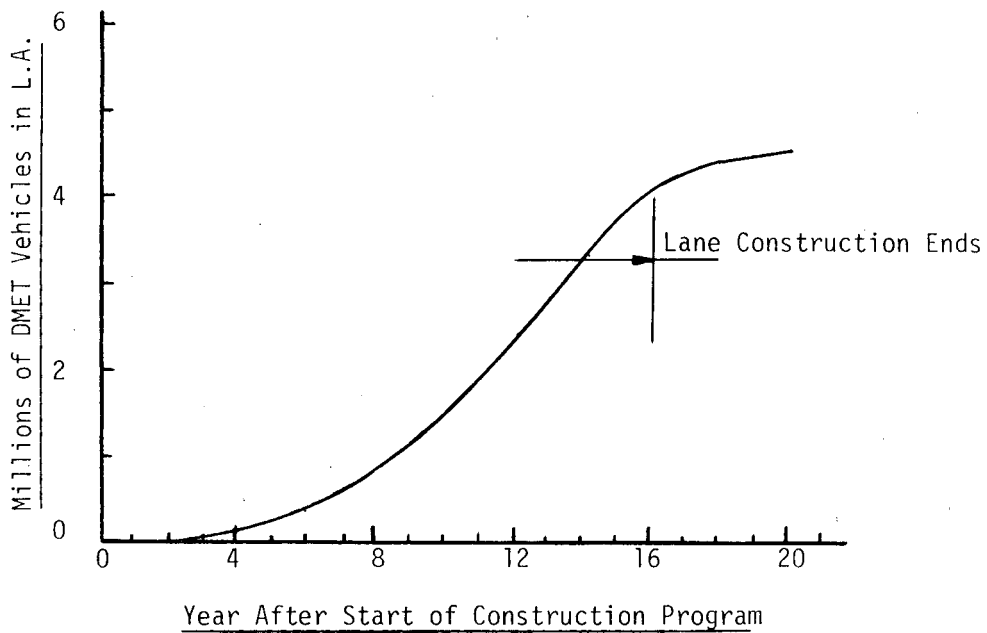


Fig. 7.4. Estimated DMET vehicle population growth vs time after start of construction. (XBL 774-787)

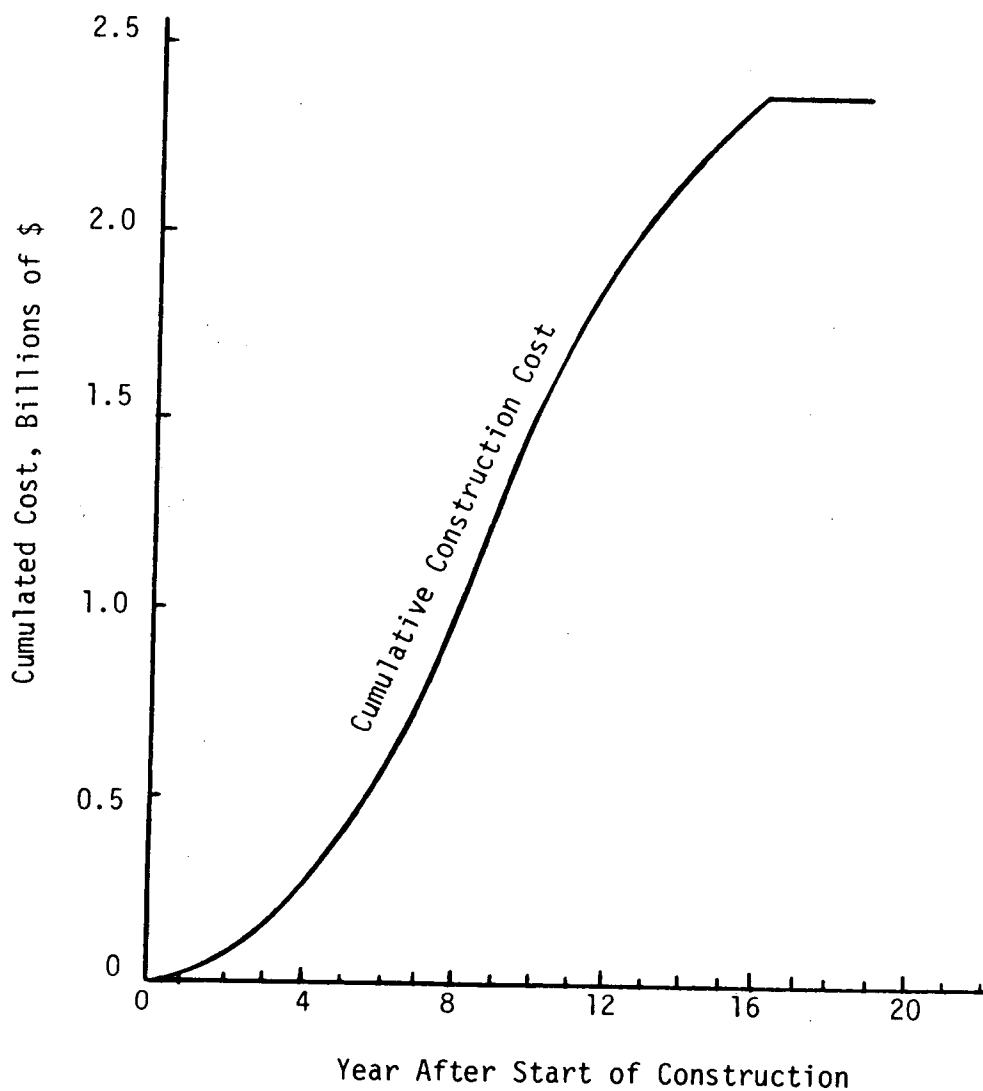


Fig. 7.5. Cumulative construction cost of DMET power system in Los Angeles vs year after start of construction. (XBL 774-788)

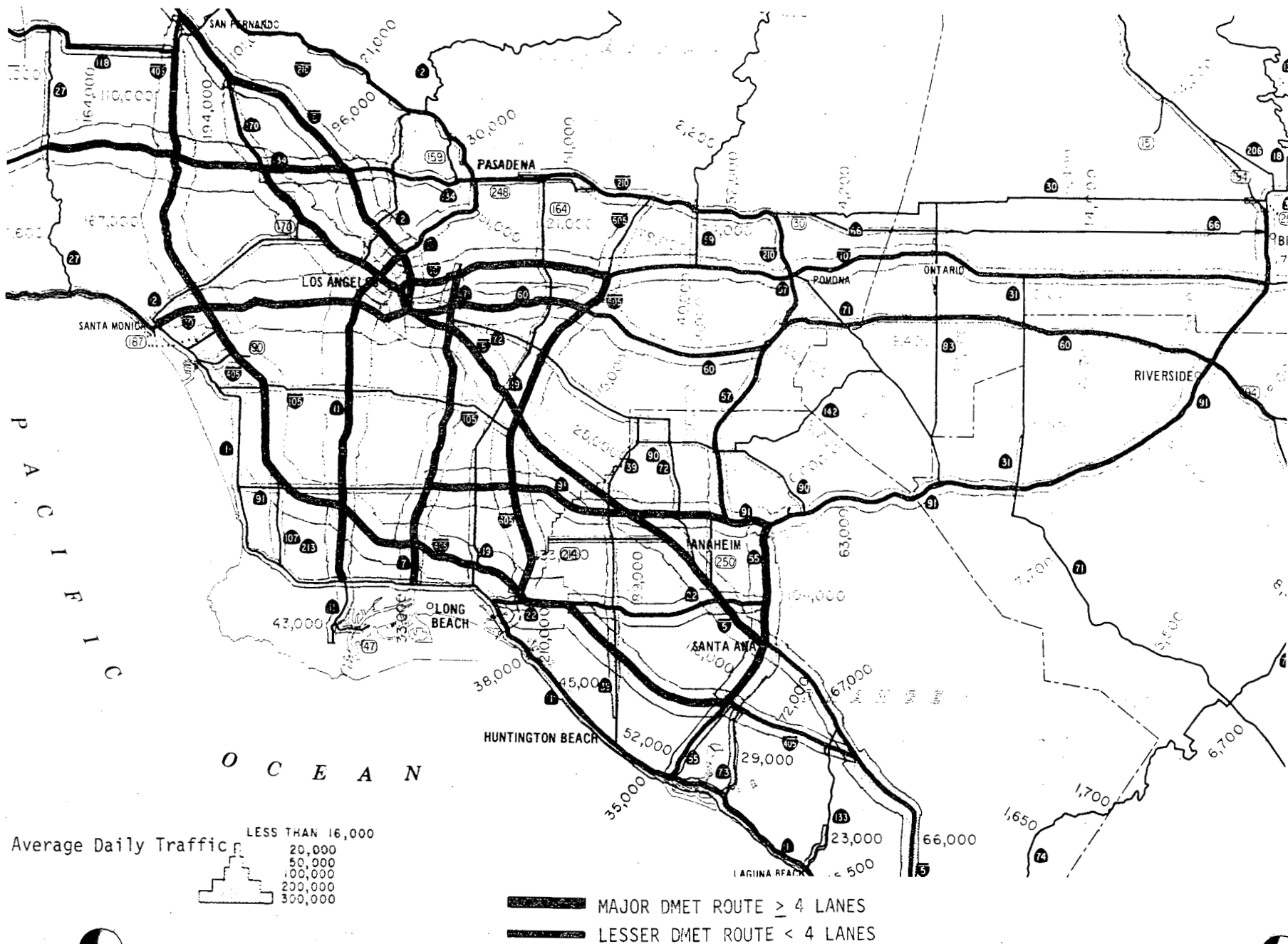


Fig. 7.6. DMET roadway network in the Los Angeles area. (XBL 774-789)

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