Title
TESTING A PROTOTYPE INDUCTIVE POWER COUPLING FOR AN ELECTRIC HIGHWAY SYSTEM

Author
Bolger, J.G.

Publication Date
1978-12-01

To be presented at the IEEE 29th Annual
Vehicle Technology Conference, Chicago,
Ill., March 28-30, 1979

TESTING A PROTOTYPE INDUCTIVE POWER COUPLING FOR AN ELECTRIC HIGHWAY SYSTEM

J. G. Bolger, L. S. Ng,
D. B. Turner, and R. I. Wallace

December 1978

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

Testing a Prototype Inductive Power Coupling For an Electric Highway System*

J.G. Bolger
Engineering Consultant
Orinda, California

L.S. Ng, D.B. Turner, R.I. Wallace
Lawrence Berkeley Laboratory
University of California, Berkeley

To be Presented at the 29th IEEE Vehicular Technology Conference

Arlington Heights, Illinois
March 28-38, 1979

*Work performed under the auspices of the Department of Energy.

Summary

A Dual Mode Electric Transportation (DMET) system is under development in which energy is electromagnetically transferred from a powered roadway to moving vehicles without mechanical contact. Energy from the roadway can be used for high-speed, long-range travel, and for replenishing energy stored in the vehicle in batteries or flywheels. The stored energy is then availble for short-range travel off the powered highway network.

A static prototype of the inductive power coupling has been built and tested. Power transfer was demonstrated to conform to the models developed in an earlier phase of the project. The prototype was used to study the power of coupling mechanism and resulting design improvements are incorporated. Tests of properties of the coupling included electrical characterization of the prototype equipment, measurements of the magnetic force between power source and pickup, measurements of coupled power versus pickup airgap and offset, measurements of magnetic flux in and around the prototype, and measurements of thermal effects induced by coupled power. The tests resulted in several design improvements which were incorporated into the coupling design.

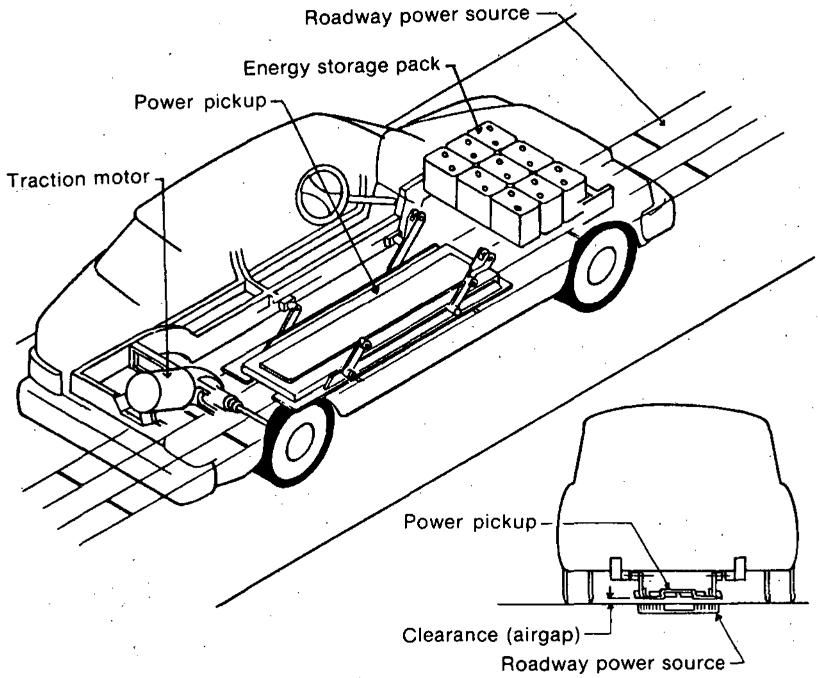
Results from the power coupling study were used to aid in the design of the dynamic prototype, in which a fifty meter powered test track and electric car with power pickup will be tested.

Introduction

There is a continuing interest in transportation systems that can improve on the performance of the personal internal combustion engine powered car in and around cities. The growing social, political, and economic costs of petroleum-based transportation provide strong incentives to develop electric transportation technology. The sharply increasing traffic on expressways spurs the development and installation of improved public transportation on the one hand, and continued pressure for expressway construction on the other. In light of the growing resistance to expressway construction in cities, automatic control of traffic, yielding greater traffic densities per lane, is seen as an alternative to the construction of more lanes. Thus, several forms of automatic electric transportation are proposed as solutions to current and future problems of public and private transport.

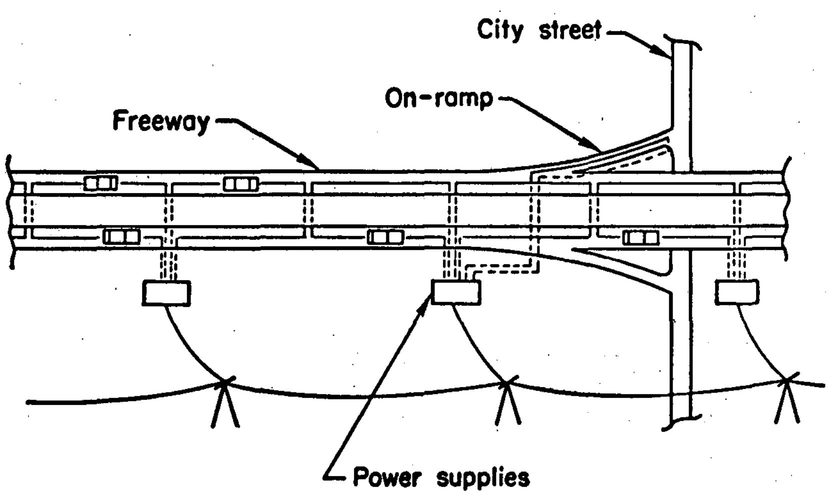
An inductive power coupling, investigated at the Lawrence Berkeley Laboratory under Department of Energy sponsorship, has characteristics well-suited to many types of transportation systems, and is particulary suited to the development of an electric (and if desired, automatically controlled) replacement for the urban commuters' gasoline cars. This inductive coupling provides for the contactless transfer of electric power from a source buried beneath the roadway surface to a pickup suspended beneath the travelling vehicle. This paper describes tests made on a static prototype of this power coupling, and the work in progress on the dynamic prototype, a fifty meter powered roadway and electric vehicle. The static prototype test results support the predictions of an earlier feasibility investigation,[1] which contained preliminary designs for the power coupling, modelled the electrical and magnetic characteristics of that structure, and proposed a scheme for making substantial use of the coupling.

The feasibility investigtion considered a Dual Mode Electric Transportation (DMET) system based on a continuous roadway power source and electric car carrying a power pickup, shown in figure 1. When the vehicle is travelling on a powered roadway, energy is available to propel the vehicle at high speed and to recharge the vehicle's energy storage pack--batteries or flywheel. Stored energy is then available to move the car off the arterial powered roadway. Figure 2 is a schematic of the roadway power system. It shows roadside power conditioners driving mile-long loops on freeways, with cars receiving coupled power. Note also the powered approach ramp. A vehicle driving on city streets on energy from its battery pack lowers its pickup from the retracted position as it enters the ramp, thereby receiving power to accelerate to freeway speeds. The provision of coupled power allows the DMET vehicle to overcome the range and performance limitations of battery powered electric cars.



XBL 786-9045

Figure 1. Inductive power coupling for electric vehicles.



XBL 774-737

Figure 2. Highway for inductively coupled cars.

A cross-sectional view of the prototype source and pickup is shown in Figure 3. The coupling mechanism is similar to that in conventional power transformers. The source is installed with its upper surface flush with the roadway. The pickup is suspended from the car approximately three centimeters above the roadway surface. Both the source and pickup are constructed of laminated transformer steel, together with suitable windings. The source conductor carries 900 A at a frequency of 180 Hz. When the pickup is in the position shown in Figure 1, the magnetic circuit is completed through the air gap. The resulting magnetic flux links the pickup winding, inducing current flow in the pickup. Coupled voltage is controlled by varying the capacitance in the pickup circuit. The power capacity of the pickup is proportional to its length. Small automobiles require approximately 20 kW to travel at 55 mph. This can be supplied by a pickup about 2 meters in length.

The installed cost of a lane-mile of powered freeway was estimated in the feasibility investigation to be $350,000 in 1976 dollars. The cost of manufacturing a car with power pickup and control was estimated to be more than a gasoline powered car, but less than a car powered only by batteries.

Figure 4 summarizes the projected electrical performance of the roadway system. Standby loss per mile is about the equivalent of one car drawing full power. Other losses increase slowly as the amount of power coupled to vehicles increases. For a roadway serving the daily traffic load of a California freeway, the average daily efficiency approaches 90%.

Testing the Static Prototype

A static prototype of the inductive power coupling was installed at the Lawrence Berkeley Laboratory. Figure 5 shows the arrangement of the equipment in the work area.

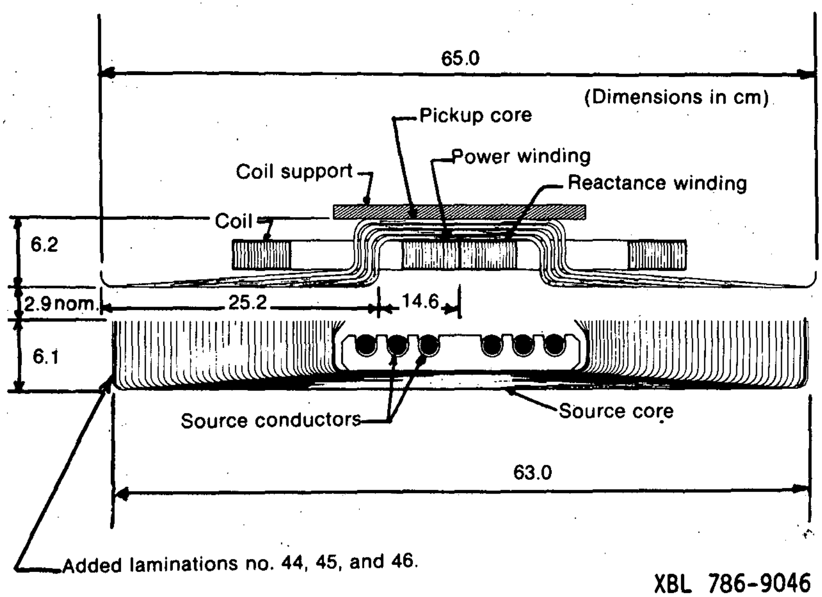


Figure 3. Cross section of the prototype coupling.

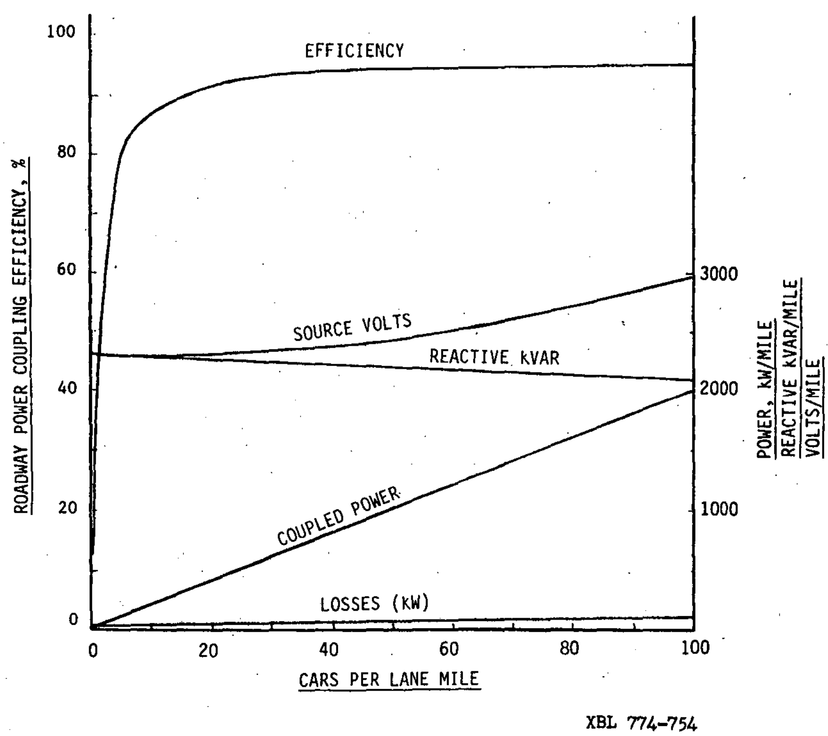


Figure 4. Characteristics of the roadway source versus traffic load.

The power coupling prototype consisted of a length of roadway power source and a short power pickup. Figure 3 shows a cross section of this prototype, which was designed to model in full scale a section of a coupling suitable for highway use. The source core was 230 cm long and the pickup core was 77 cm long.

A pickup suitable for a compact automobile would be more than twice the length of the prototype. Because the power capacity of the coupling is directly proportional to its length, it was feasible to employ the shorter, less expensive prototype without compromising the utility of the test results. Figure 6 is a schematic of the prototype power coupling.

The source loop was excited by a motor-generator set capable of generating power over the 150-210 Hz frequency range. The pickup was equipped with a variable capacitor bank to control voltage induced in the pickup circuit. The pickup could be loaded either with a resistance load or a circuit to simulate battery charging load. The test facility also included an array of instrumentation for measuring currents, voltages, power, phase relationships, and magnetic fields.

A number of tests of the fundamental properties of the inductive coupling were performed at the static prototype facility. The test results were used to characterize the inductive coupling,to provide information needed by designers of inductive coupled transportation systems, and to improve the design of the power coupling components. The static prototype was used to measure:

a) Electrical Performance. Parametric values of the coupling and power transfer controllability were measured. Loss measurements and a loss reconciliation were made. A simulated battery charger and motor load was applied to the pickup circuit. Particular attention was paid to the variation in coupling parameters induced by changes in lateral offset and vertical gap between the source and pickup.

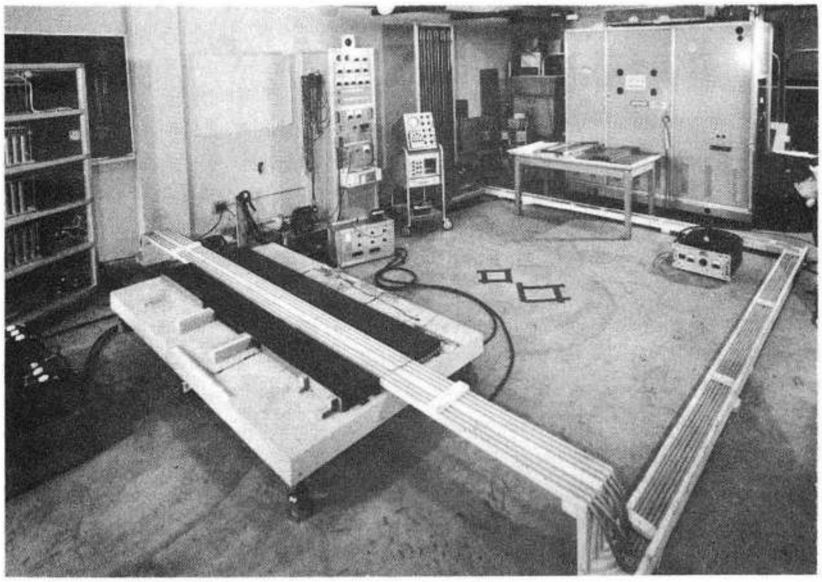
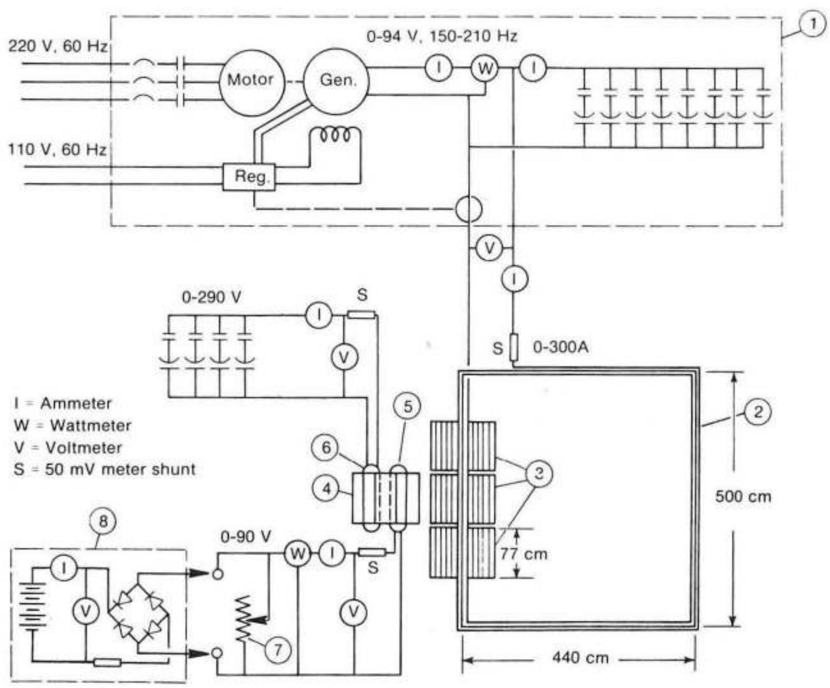


Figure 5. Arrangement of the static prototype facility.



XBL 786-9180

Figure 6. Schematic of power coupling prototype system: 1. Power supply; 2. Source conductor loop; 3. Source cores (3); 4. Pickup core; 5. Power winding; 6. Reactance winding; 7. Resistive load; 8. Vehicle energy storage simulator.

b) Magnetic Field. Magnetic field profiles were taken for the source in both the coupled and uncoupled condition. Extensive measurements were made of the magnetic flux distribution in the steel cores of source and pickup, leading to design refinements.

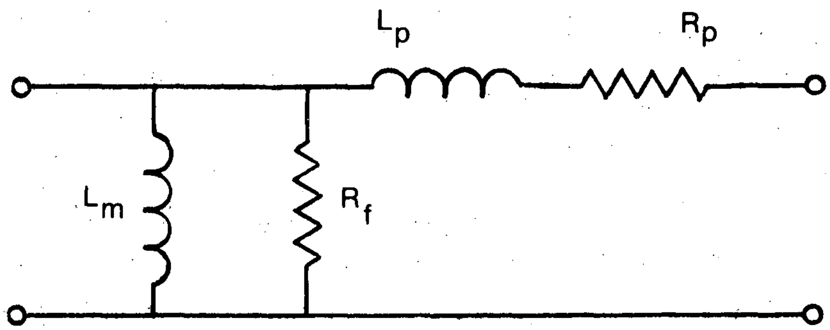
c) Magnetic Force. Measurements were made of the vertical attractive force and lateral centering force between source and pickup.

d) Thermal and Acoustic Effects. Measurements were made of heating caused by energy transferred from the source's magnetic field to nearby steel structures. Some acoustic effects were examined.

<u>Electrical Performance</u>

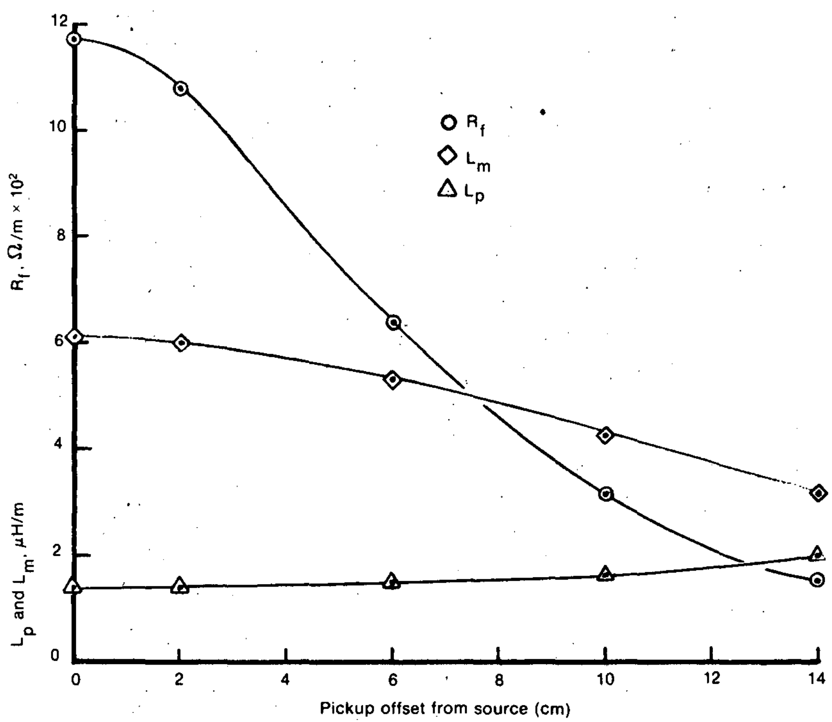
The static prototype schematic in Figure 6 shows the coupling apparatus and the points where the electrical measurement were made. The prototype was first used to characterize the inductive and resistive parameters of the coupling itself. The model is similar to that of a power transformer driven by a current source[1,3]. Figure 7 shows the equivalent circuit. Because the coupling was driven by a current source, the primary leakage inductance and resistance do not affect the coupling itself, but cause losses in the source power circuit. The usual open- and short-circuit measurements were made to characterize this coupling. The mutual inductance L_m and the coupling leakage inductance L_p are measures of power transfer capability, while the core loss resistance R_f, and the copper loss resistance R_p model the circuit losses. These four parameters are fundamental measures of the characteristics of the coupling.

Figure 8 shows the relationships of R_f, L_m, and L_p as the pickup is displaced laterally from the center of the source. The



XBL 786-9177

Figure 7. Equivalent circuit of the power coupling.



XBL 786-9178

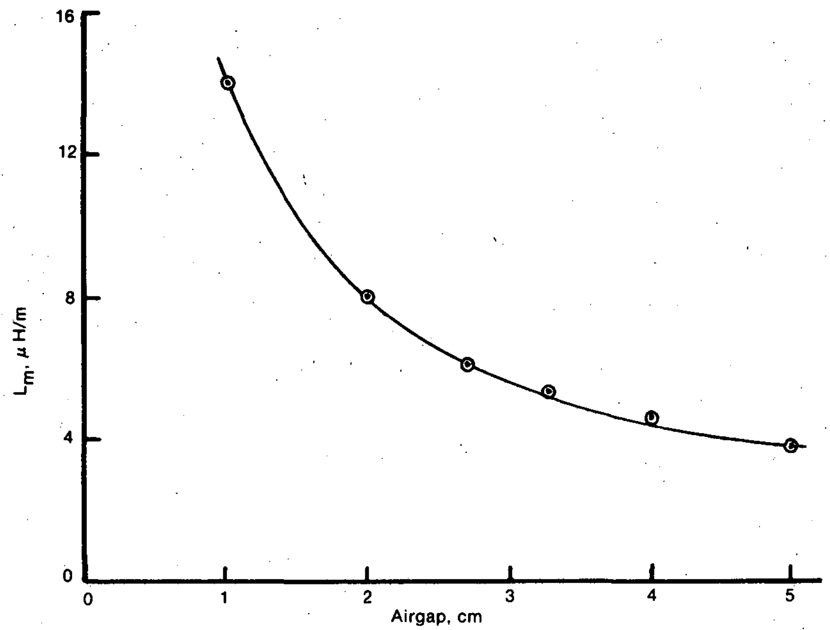
Figure 8. Electrical characteristics of the coupling vs. pickup offset.

initial value of the mutual inductance Lm agrees closely with the prediction of the feasibility investigation. The ratio $L_m/(L_m + L_p)$ gives the fraction of flux which links the source and pickup. A large fraction reflects good coupling, indicating full utilization of magnetic materials for power transfer. For a typical power transformer, L_p is small, and the ratio is nearly 1.0. For the inductive power coupling at zero offset, the ratio is about 0.83. This indicates that the coupling design achieves the needed power transfer level at a reasonable materials cost and level of complexity. As the pickup offset is increased, the ratio decreases. Thus, increasing pickup offset caused by driver steering gradually reduces the power available to the vehicle.

Core loss is greater than copper loss in the coupling. Also, copper loss is independent of offset. Figure 8 shows that R_f is large at zero offset, indicating that loss is a small percentage of the transferred power. As offset increases, R_f decreases and power loss increases. At 14 cm. offset, R_f is reduced to the same order of magnitude as the impedance of the mutual inductance, and a significant fraction of the transferred power is dissipated in the core. Thus, efficiency also decreases gradually with offset.

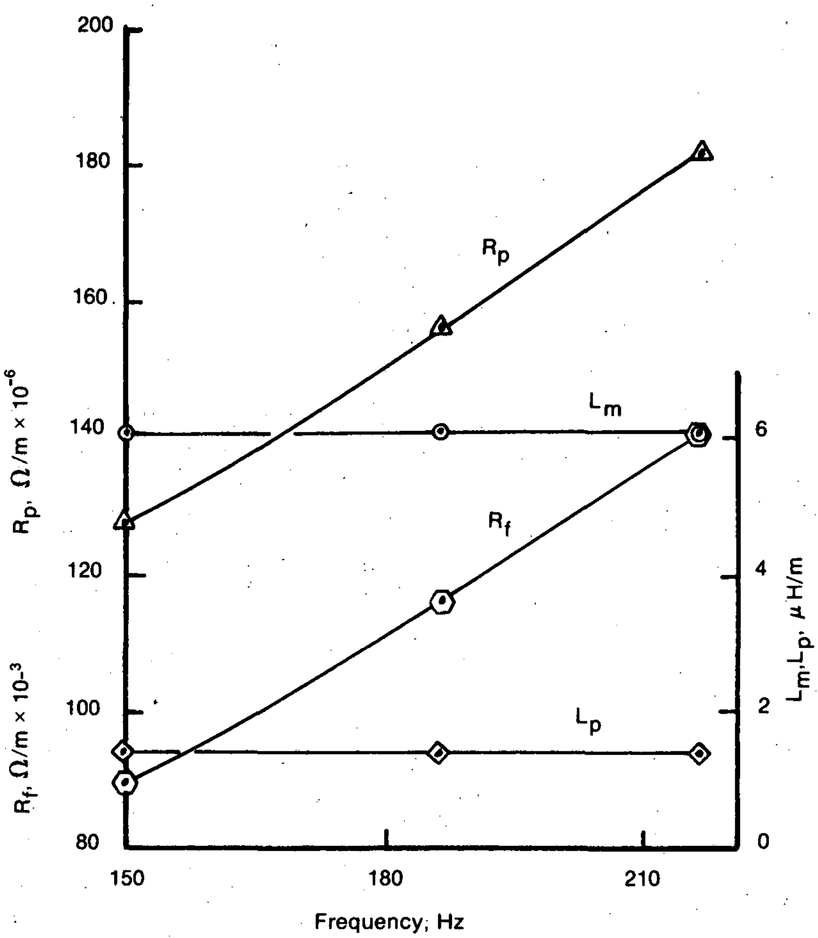
Figure 9 confirms the early prediction of the relation between mutual inductance of the coupling and the airgap between pickup and source. The nominal airgap for this design is three centimeters. Because this is beyond the "knee" of the curve, further increases in gap cause only a gradual decrease in coupling. Thus, implementations of this power coupling which require a greater nominal gap can be achieved without major design compromises.

Figure 10 shows the relationships of the four basic parameters to frequency. As expected, the inductances are constant. The copper loss resistance increases with frequency because of the skin effect in the conductor. However, the core loss resistance increases with frequency, because eddy current and hysteresis losses decrease for constant induced voltage. Thus, there is a range in which change in frequency causes small changes in efficiency.



XBL 786-9052

Figure 9. Mutual inductance of the coupling vs. airgap.



XBL 786-9053

Figure 10. Electrical charcteristics of the coupling vs. frequency.

The choice of 180 Hz, the third harmonic of 60 Hz, is a convenient value in that range.

The design of the source and pickup cores, the choice of the drive frequency of the source current, and the tolerance of the coupling to variations in lateral offset and vertical gap of the pickup can all be evaluated in terms of the relations between L_m, L_p, R_p, and R_f. The values measured on the existing prototype indicate a very useful capability for power transfer. However, there are strong indications that further design studies could improve efficiency, reduce cost, and expand operating tolerances for gap and offset.

Efficiency of the inductive power coupling in a transportation system is one of the most important parameters studied on the static prototype. Because the pickup length and construction details of the prototype were not the same as that of a proposed highway, certain losses were particular to the test setup. A detailed electrial model of the static prototype which accounted for all the losses in the system was constructed. Measurements were made of the power lost in each of the system elements. In each of several cases, all the input power was accounted for to within the accuracy of the measuring instruments. This confirms the accuracy and completeness of the prototype model.

The largest loss in the prototype is in the source conductors. It is a higher fraction than that predicted for a highway system, since conductors of small cross-section were chosen because of availability and ease of handling. Other losses were core loss, cabling losses in both the source and pickup circuits, pickup conductor loss, and capacitor losses. Figure 11 shows the overall efficiency of the prototype. Efficiencies range between 70 and 50% at zero offset, depending on induced pickup voltage. These figures demonstrate that the efficiency model of the feasibility investigation is accurate. As such, they confirm the efficiency projections of about 90% for an electric highway system.

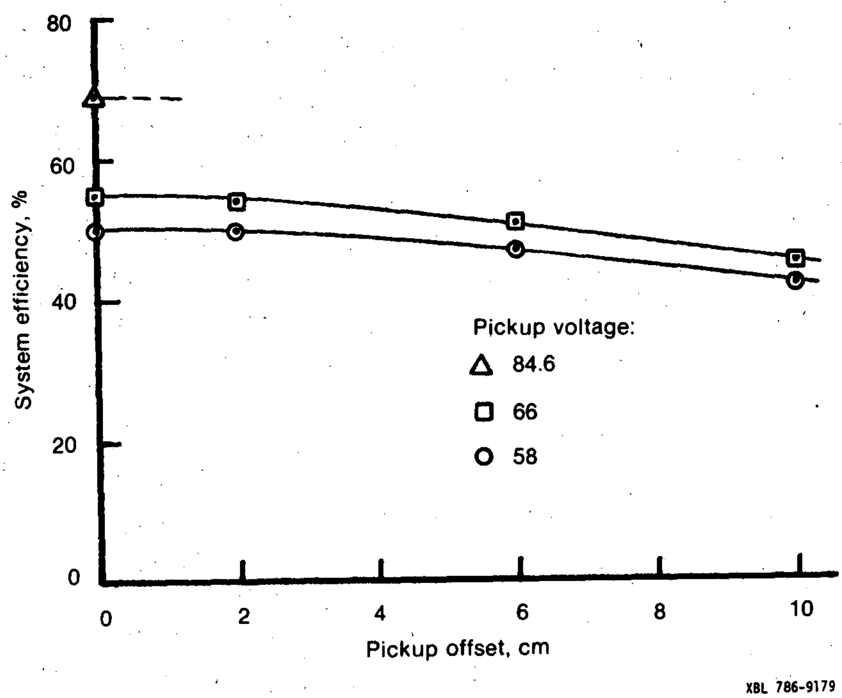


Figure 11. Prototype system efficiency vs. pickup offset.

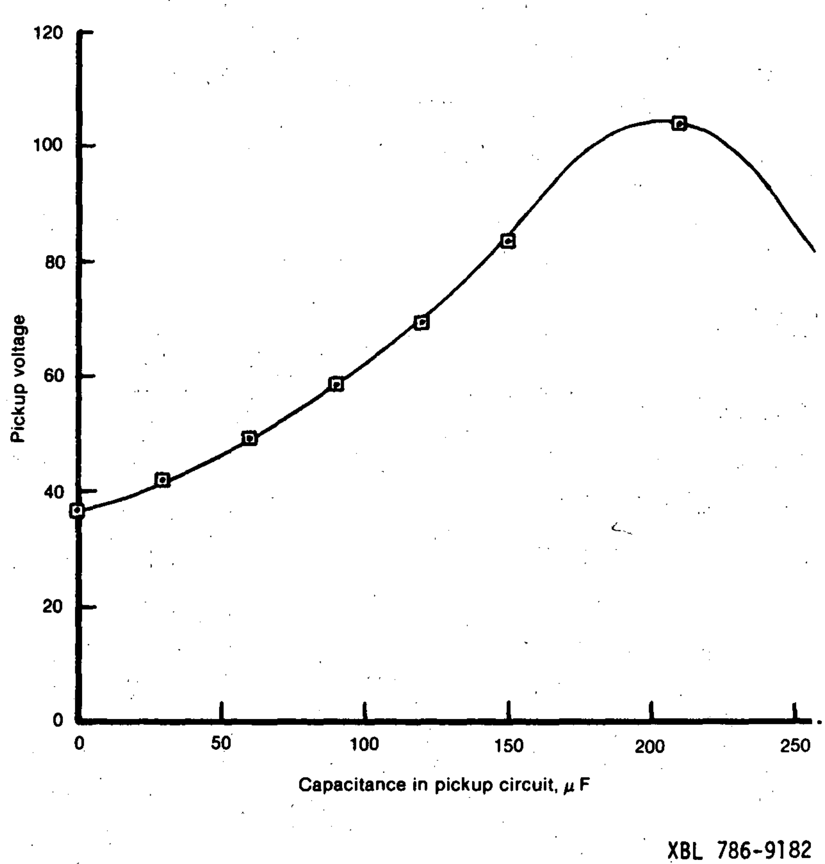


Figure 12. Pickup voltage vs. capacitance in pickup circuit.

Control of power flow from source to pickup is an important capability of the system. The feasibility investigtion proposed a vehicle power system in which the alternating current from the pickup is rectified for charging the battery and driving a dc motor. Variations in the coupling caused by offset, gap, and load current must be compensated in order to maintain a constant output voltage. This compensation is provided by varying capacitive loading of the pickup. This capacitive compenstion controls the output voltage by bringing the coupling circuit closer to resonance.

Figure 12 is a plot of the voltage induced across a fixed load resistance versus capacitance in the pickup circuit. Control of the level of coupled voltage over a 2 1/2:1 range is demonstrated. Note the resonance condition at 200 uf control capacitance.

A test was made of a coupled pickup with a load consisting of a battery pack (charging load) and resistor simulating a motor load. The power delivered by the pickup decreased about 10%, compared to a purely resistive load. This resulted from the reduced conduction angle of the rectifiers into the constant voltage load. Capacitive control of delivered power was effective over the full range. Waveforms are given in reference 2.

Magnetic Field

The linking magnetic field is the mechanism of power transfer in this inductive power coupling. It is necessary to characterize the magnetic field in and around the structures of the coupling to understand its performance.

The macroscopic effects of the magnetic field are those effects measurable outside the structures of the source and pickup. Figure 13 shows a test fixture used to measure the magnetic field around the coupling. Two magnetic flux probes, sensitive to horizontal and vertical magnetic field components respectively, were mounted at the end of the probe positioning rod. The probes were swept across the

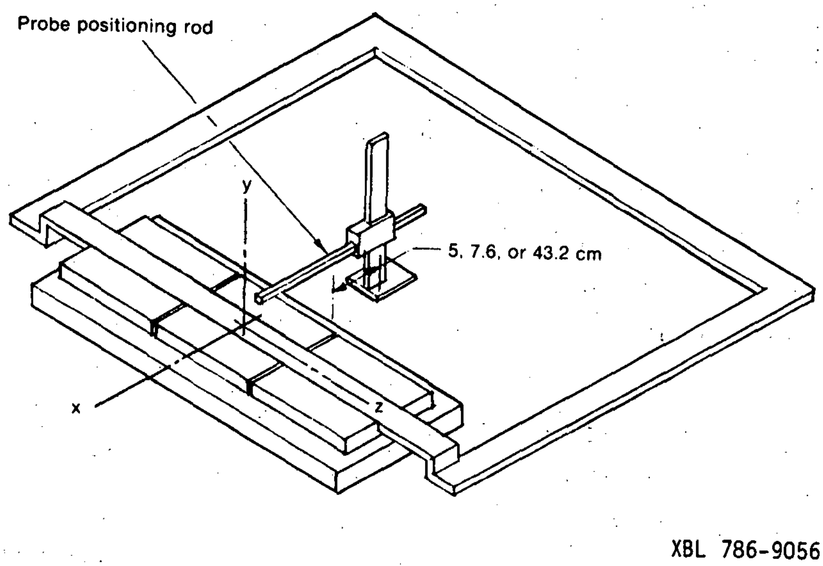


Figure 13. Magnetic measurements probe.

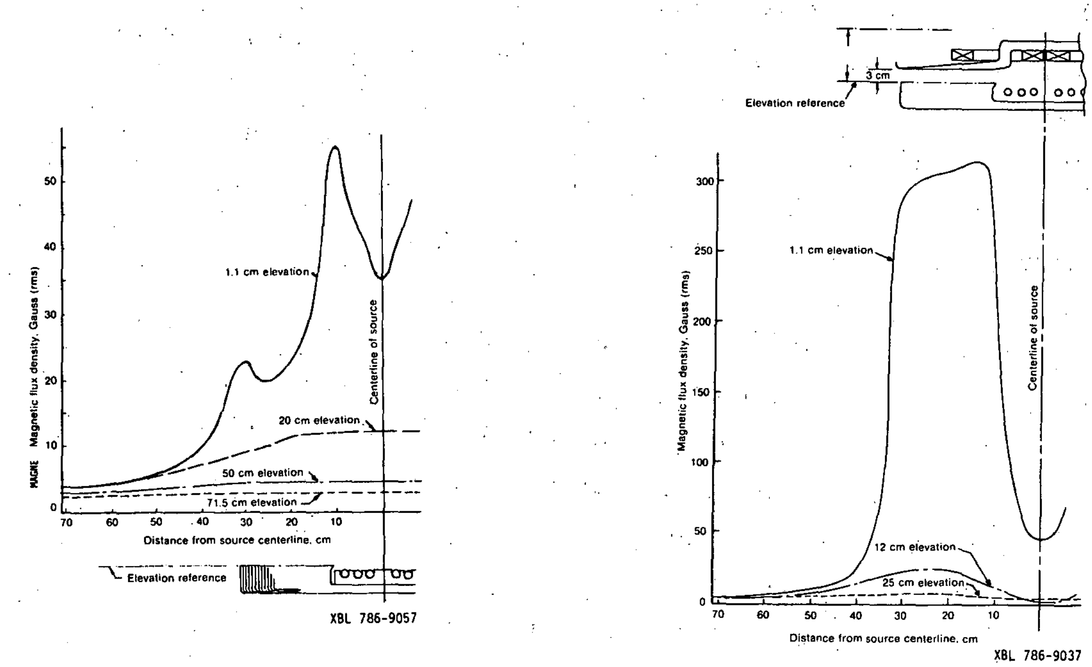


Figure 14. Magnetic flux density above the uncoupled source (left) and coupled source (right) vs. distance from source centerline, at various elevations.

source at several elevations above the source, in both the coupled and uncoupled condition. The field profiles of Figures 14 were constructed from data from these scans.

Several facts of interest can be noted from these plots. Flux densities as high as 400 gauss occur only in the airgap of the coupled source. Moderate flux levels (10-60 gauss) occur on an uncoupled roadway close to the surface and near the edges of the core section. At distances more than a meter away from the center of the roadway, the flux level is about the same as the earth's magnetic field (1-2 gauss). These observations indicate that the fields to which the public would be subjected by an inductive power coupling are not greater than those of traditional power systems. However, further study is still required on the long-term biological and environmental effects of these to low-level ac magnetic fields.

It is also necessary to study the microscopic effects of the power coupling mechanism. In particular, an optimized design has an even flux distribution inside the steel laminations of the source and pickup cores. An area of higher flux density indicates increased iron losses while a lower flux density indicates under-utilization of materials. To measure the flux, coils are wrapped around the laminations of interest. The flux in a given lamination can then be calculated from the voltage induced on the test coil, the cross-sectional area of the lamination, and the source current frequency.

This measurement technique indicated excessive flux levels in some of the outside laminations of the original design. Additional laminations were added to modified cores. Figure 15 shows the flux concentration in the modified source cores. No excessive flux concentrations exist, but the laminations closest to the conductor slot carry less flux than the rest. A further design refinement using fewer lamiantions near the center provided a more uniform distribution.

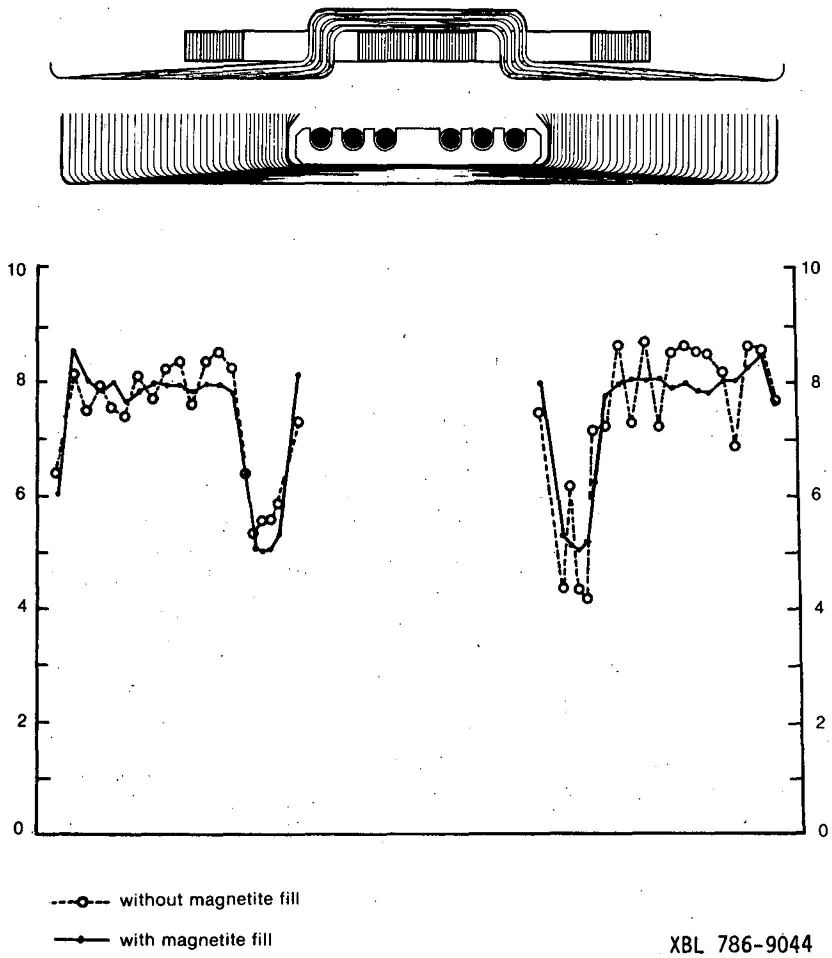


Figure 15. Magnetic flux density in source core laminations with centered pickup, with and without magnetite fill.

In a highway application of this technology, the spaces between the laminations must be filled with a material capable of bearing traffic weight loads. A mixture of cement and magnetite filler was proposed to achieve the needed strength and improve the magnetic properties of the coupling. Figure 15 also shows the results of filling the source core with loose magnetite filler. In addition to reducing the reluctance of the core, the magnetite fill also smooths out the magnetic flux in the laminations. Further study is required to obtain an optimal design of source core and roadway materials.

Magnetic Force

The magnetic field linking the source and pickup creates an attractive force between them. This force pulls the pickup downward toward the source. If the pickup is offset from the centerline of the source, a horizontal centering force is present. These forces are of concern because they could influence the handling and ride quality of the vehicle to which the pickup is attached, and because they influence the structural requirements for the pickup suspension.

Measurements of the horizontal and vertical components of the magnetic force were made on the static prototype. The force is proportional to the square of the flux density at the pole face. For a given structure, flux density is also proportional to coupled voltage. Design improvements to the model suggested by earlier investigation were incorporated in the prototype source and pickup. These changes reduced the magnetic force by increasing the pole face area, thereby reducing the flux density.

The vertical force was less than 20 kg at full voltage. Scaling this force for a pickup 2 m long results in a vertical force of 50 kg for a compact car. The horizontal magnetic force measured on the pickup was less than 4 kg. Again, scaling for a compact car, a horizontal centering force of 10 kg is expected. Forces of this magnitude should cause little concern for the directional stability and controllability of coupled vehicles.

Thermal and Acoustic Effects

The steel structures of vehicles operating over a powered source provide a low reluctance path for magnetic flux. The alternating flux flowing in these paths causes both hysteresis and eddy current losses in the steel, resulting in heating.

To evaluate the magnitude of this heating, a 22-gage (0.75 mm thick) steel sheet was supported over the prototype source at several elevations. The sheet was equipped with thermocouples and flux measurement coils. These sensors were used to determine the rate of temperature rise and the magnetic flux in the sheet.

Figure 16 shows the variation of temperature at the centerline of the sheet versus the elevation above the source, after steady state conditions were reached. At the elevation of the floor of a typical automobile, i.e., about 23 cm, a stationary bare steel sheet with natural convective cooling on its upper surface only reached a temperature of 58 ^{o}C. It is difficult to compare this temperature rise to that of a formed, painted, carpeted floor pan of a car. The forced convective cooling on the lower side is likely to be significant. Further tests in which an instrumented car is driven and parked over an operating source are necessary. A steel sheet resting directly on the source reached a temperature of about 192^{o}C. This temperature does not ignite ordinary materials.

The heating of a steel fuel tank slung below a vehicle could be of concern if its lower surface were close to the road. A preliminary test was made of the effectiveness of an expanded metal magnetic shield in reducing the thermal input. The position and material of the shield were not optimized. The temperature rise in the 0.75 mm steel sheet above the shield reached a maximum of 23^{o}C; without the shield, the temperature rise was 35^{o}C. The test indicated that simple shields can be employed to advantage where local heating is of concern.

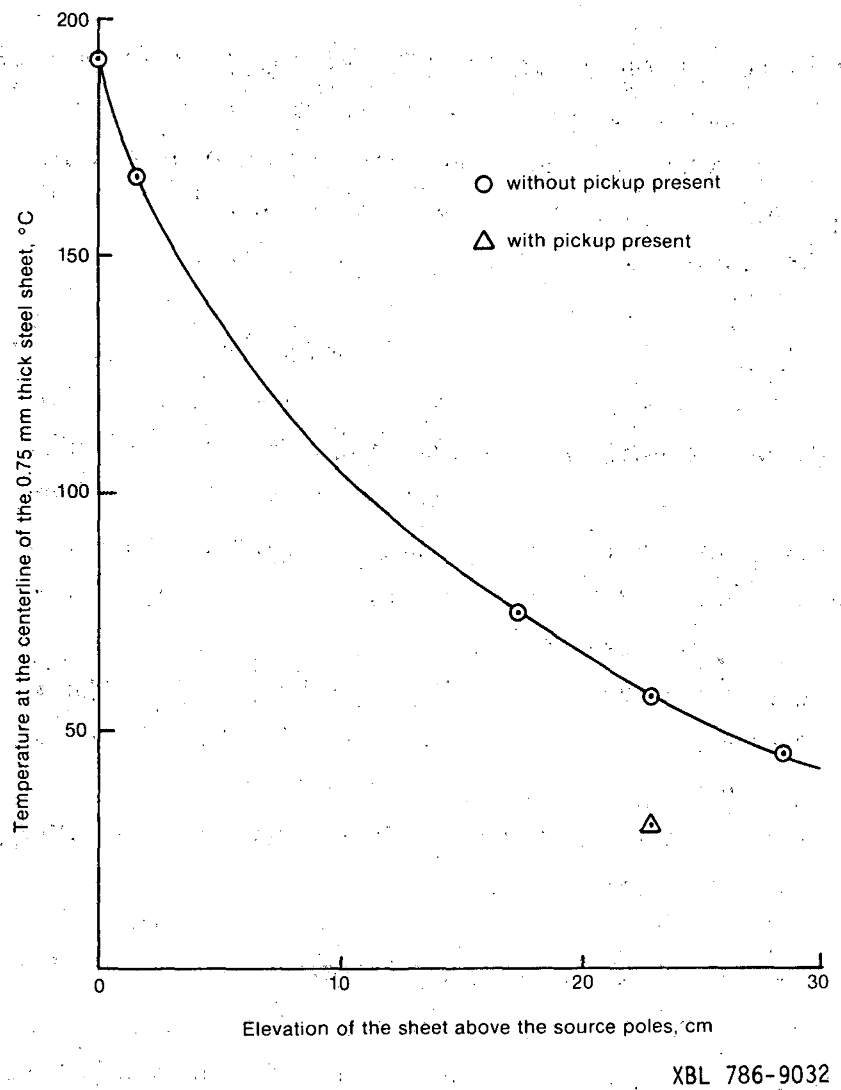


Figure 16. Temperature at the centerline of a 0.75 mm thick steel sheet above the source vs. elevation of the sheet.

Tests were also made on a steel-belted radial tire centered over the source. This represents a "worst case" with respect to power dissipation in the steel belt. Temperature rise was localized to the region of contact with the road. There the temperature rose 20°C in an hour. This effect is small compared to the heating effect of flexural losses in the tire.

The prototype configuration was quite noisy. The following factors contributed to the noise output:

(1) The source and pickup were initially supported on plywood structures that amplified vibrations.

(2) The source laminations had no transverse damping.

(3) Flux concentrations occurred near the thin outer edges of the pickup that increased magnetostriction amplitudes and consequent vibrations of the pickup edges.

(4) The prototype was installed in a small room with bare walls.

The flux concentrations in the outer laminations of the pickup core were reduced, by adding laminations. This produced a large reduction in the vibration amplitude in the pickup core. Filling the source core with usual highway construction materials is expected to provide the damping necessary to reduce acoustic energy from the coupling to a very low level.

The Dynamic Prototype

A design for a dynamic prototype facility has been developed. This facility will allow testing of inductive power coupling between a powered roadway and an electric vehicle. The facility will include a powered roadway fifty meters long, an electric vehicle equipped with a battery and pickup, and the instrumentation and controls necessary to acquire data on the system under dynamic conditions.

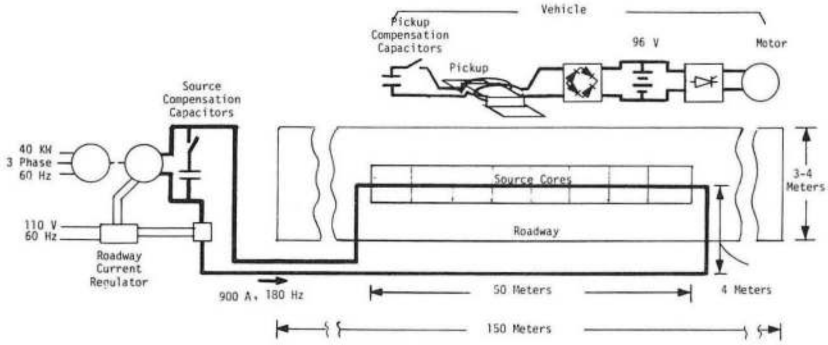
The test vehicle is a modified 1969 Volkswagen Type 3 chassis. The body and engine were removed, and a sturdy frame and roll cage were built around the remaining chassis components. It is equipped with an 8 HP series-wound, DC traction motor with a chopper controller, eight 12 volt traction batteries, a pickup suspension system, and space for electronic and electrical instrumentation. Particular attention was paid to maintaining the driving characteristics of the vehicle.

Figure 17 is a photo of the vehicle. The chopper is located in the box to the left of the motor. Commutating capacitors, and inductors are in the box to the right of the motor. The two battery trays are located on each side of the vehicle. Table 1 lists the vehicle specifications.

The pickup on the vehicle will have a cross-section similar to that used in the static prototype. It will be twice as long, allowing 16 kw of power to be coupled. Table 2 summarizes the pickup's characteristics. Associated with the vehicle's reactance winding is the pickup's compensation capacitor bank. Provision will be made to allow manual and automatic switching of various capacitors across the winding.

The pickup suspension will allow the pickup to be lowered to the coupling position and raised for travel off the powered roadway. It will also compensate for action in the vehicle's suspension under dynamic conditions. Provision will also be made to lock out the pickup suspension and thereby fix the pickup at any desired height above the roadway surface.

Figure 17. The dynamic prototype test vehicle.



Dynamic Prototype - 50 Meter Powered Roadway

XBL 7812-14049

Figure 18.

The proposed 50 meter test roadway section is illustrated schematically in Figure 18. A motor generator will produce 900A of 180 Hz roadway source current. The source conductor will consist of six stranded aluminum conductors connected in parallel. Compensation for the roadway's inductive load is provided by a source capacitor bank connected in parallel with the roadway loop.

A cross section of a proposed roadway design is shown in Figure 19. The source cores will be laid in a slot formed into a concrete slab. The source conductor, suitably insulated, will be laid in place in the cores. The cores will then be grouted in the slot. The running surface above the source will be a reinforced fabric covered by an asphalt slurry sealcoat.

The test program for the proposed dynamic prototype will include measurements of dynamic power coupling capability; electrical and magnetic characterization of the prototype, with particular emphasis on electromagnetic interference induced in nearby structures; and vehicle suspension tests.

Table 1

Vehicle Specifications

Weight	3000 lbs. (1350 kg)
Motor Type	Baldor Traction Motor, 8 HP, 72V, 3200 RPM
Chopper	Sevcon Model 7800-4; 96V @ 250A
Speed Range	0-30 mph, (0-50 kph)
Battery Pack, 96 volt	Trojan Type RV27P-UT; 12V, 95 AH; 8 each
Chassis	Volkswagen Type 3, 1969

Table 2

Pickup Specifications

Weight	270 lbs. (120 kg)
Length	154 cm
Width	65 cm
Power Winding	Aluminum, 6 turns with taps at 4 and 5
Reactance Winding	Aluminum, 18 turns
Volts per Turn	18 volts
Power Output Rating, Nominal	16 kw

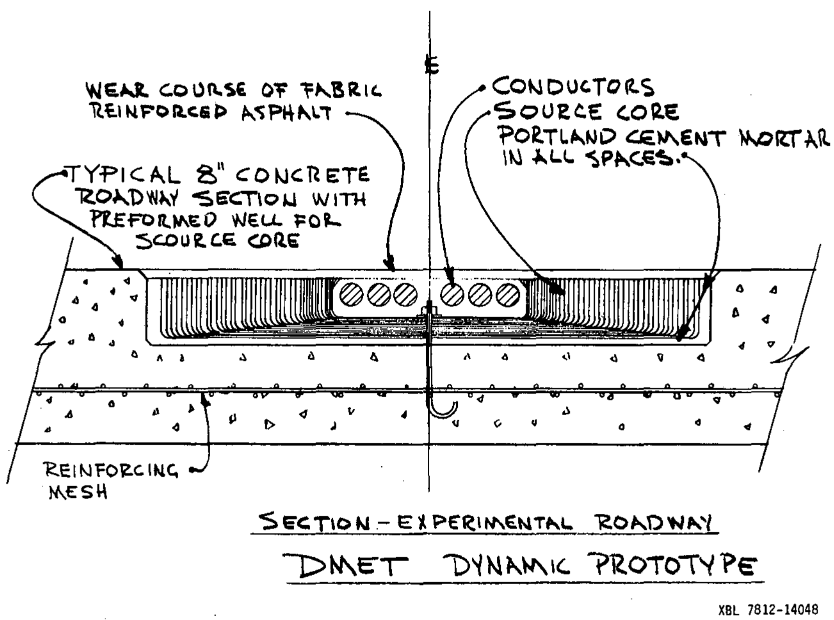


Figure 19.

References

1. J.G. Bolger and F. Kirsten, "Investigation of the Feasibility of a Dual Mode Electric Transporation System," Lawrence Berkeley Laboratory Report, LBL 6301 (1977).

2. J.G. Bolger, M.I. Green, L.S. Ng, and R.I. Wallace, "Test of the Performance and Characteristics of a Prototype Inductive Power Coupling for Electric Highway Systems," Lawrence Berkeley Laboratory, LBL-7522 (1978).

3. J.G. Bolger, F.A. Kirsten, and L.S. Ng, "Inductive Power Coupling for an Electric Highway System," IEEE 28th Vehicular Technology Conference (1978).

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720