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MODEL TO PREDICT PERFORMANCE OF ALL ELECTRIC TRANSPORTATION WITH WIRELESS POWER BEAMS

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ABSTRACT

A future concept transportation technology is being developed to provide all-electric vehicle recharging while traveling on the roadway for public and private vehicles, utilizing a renewable energy source. These vehicles will have the same range, power and maneuverability currently enjoyed by those powered with the internal combustion (IC) engine. The vehicles will have an electric drive motor (or motors) with minimal on-board energy storage (flywheel, capacitor, battery or fuel cell) as a reservoir when not in the range of the recharge network. The goal is to retain all the positive attributes of the IC-engine driven vehicles while eliminating pollution and dependency on hydrocarbon fuels.

The recharge network is called the Remote Charging System for a Vehicle, or simply the Vehicle Remote Charge (VRC). This is a wireless power transmission system that replenishes the on-board energy storage system of a moving (or parked) vehicle with a microwave or laser power beam. The concept of transmitting electric power using a conductorless method has been in existence since the early 1900s. In the 1960s the idea was proposed to beam orbiting satellite-collected solar energy to the surface of the earth for use in the existing electric power grid. Hence utilizing a fully integrated network from satellite-collected solar power to on-board energy storage of a moving vehicle would entail a completely pollution-free, renewable energy transportation system for the country. Research in this field is an on-going effort, and the efficacy of wireless power transmission has been demonstrated in many tests around the world. A simple power transmission model demonstrates that the wireless power beam energy can be transmitted effectively to the vehicle, providing the necessary motive power to operate the vehicle.

INTRODUCTION

Wireless communication is the technology of today. Wireless power transmission will be the technology of tomorrow in transportation. This is a clean, reliable energy source for a transportation system that will provide all the conveniences of today's vehicles, with none of the problems [Parise, 1998].

Current non-polluting vehicle designs have many issues that must be overcome before the systems will be accepted by the public. Vehicle range with quick recharge and maneuverability are two qualities the American public has come to enjoy and expect. Battery driven vehicles have a limited range of 80-100 miles before a recharge is required -- a process that can take up to 16 hours.

The use of fuel cells shows promise for mobility and convenience, but has many issues concerning limited on-board storage and fuel distribution. However, the VRC can even be used to convert water into hydrogen and oxygen for fuel on the vehicle in a closed or open system. Proton Exchange Membrane technology is especially suited for this process.

In fact, the use of this new system will put ultracapacitors and flywheels in the forefront of utilization for on-board energy storage. This "refueling" technology will reduce considerably the size and complexity of on-board fuel storage required for future pollution-free automobiles. Flywheels and ultracapacitors will be as commonplace in clean operating vehicles as fuel cells and batteries.

For the VRC, the majority of the installation of the system will take place above the roadway or city sidewalks on existing power line (telephone) poles or on new stand-alone poles that would be in conjunction with the existing poles. Therefore inconvenience will be at a minimum, and costs will be reduced significantly.

The safety of the power transmission system is an all-important subject that must be considered if this transportation means is to be a serious contender in this country. Specific design features will ensure the safety of vehicle occupants, pedestrians, animals and inanimate objects, convincing even the most ardent skeptics that wireless power transmission can and will be a major contributor to transportation.

With the appropriate resources today, the VRC can be demonstrated in three years, with a full-blown downtown city bus system working in about five years. A brief description of previous research, overall system operation, means to address specifically the methods to be employed to ensure its safe operation, and a dynamic model that will be used to predict and select many of the operational parameters that will be required are presented.

SYSTEM OPERATION

Basic components of the system are shown in Figure 1. When a predetermined level of discharge is noted in the energy storage unit by the vehicle's central processing unit (CPU) in the Power Usage Monitor, a "translocator signal" (similar to a transponder signal) is triggered on the vehicle and transmitted to alert roadside power transmitters that a vehicle is present for recharge. The translocator signal identifies the vehicle as an end-user and signals the location and movement of the vehicle. The nearest Power Transmitting Unit is activated by the translocator signal, and a coded electronic link-up between the vehicle and the power transmitter commences. The Power Transmitting Unit then tracks the vehicle while following the translocator signal, aims the power beam at the power receiving antenna, and recharges the energy storage unit on the vehicle, i.e., fills the "fuel tank" [Parise, 2000a].

This electronic communication and recharge takes place as the vehicle travels adjacent to the telephone pole (or stand-alone power pole), having a wireless power transmitter mounted on it. Line-of-sight transmission is utilized between the stationary power transmitters and the power receiver on the vehicle to ensure safe, efficient power transmission to the vehicle. When out of range of the pole, the power beam is terminated. If more recharge is required, the translocator signal would continue and the next power transmitter would be activated by the vehicle. Charging is essentially passed on from pole to pole as the vehicle travels on the roadway.

Coded translocator signals identify each vehicle. The identification of the signal allows the Power Transmitting Unit to track a vehicle and trade signals among receiver/transmitters to minimize interferences and crossing of energy beams when multiple vehicles are present. The pole-mounted network will be utilized by both public and private vehicles. In addition, coded translocator guide beacons may allow user identification to electric power companies for billing purposes.

If the electronic communication and/or power beam is interrupted by any object during transmission (tree branch, wire, pigeon, etc.), the power beam is terminated immediately. However, if the translocator beacon continues to be activated, then an electronic verification and link-up would have to be re-established before the power beam recommences. This is an important safety feature of the system.

Once the energy storage reservoir on the vehicle reaches the "Full" condition, the translocator signal is terminated and power transmission stops. When more replenishing is required, the translocator signal is once again activated, and so on.

The VRC will obtain its energy directly from the electric power grid poles on which the Power Transmitting Units are mounted. In fact, it would be desirable to have the system capable of maintaining contact with the vehicle from pole to pole. This would provide a constant power transfer from electric grid to vehicle, reducing the required size of the on-board energy reservoir, and a convenient means for connecting directly to the internet through phone or cable lines.

That is, the data link between the power transmitter and the traveling vehicle can include information off the internet directly to the vehicle for driver travel information or passenger correspondence while traveling. Once this communication link is established between the traveling vehicle and land-based power transmitters, the possibilities become endless.

POWER TRANSMISSION

The efficient, reliable, safe transmission of power is critical to the success of the system. Both laser-based [Smakhtin, 1999] and microwave-based [Brown, 1973; Schlesak et al., 1988] systems have been proposed and studied. Laser systems provide small aperture and receiver sizes that would be compatible with roadside and vehicle mounting. The major concern for laser based systems has been the attenuation of the beam in the atmosphere. For space-based systems this would be a problem due to the great distances involved (hundreds of kilometers); therefore microwave energy has been the beaming method of choice.

Atmospheric attenuation of microwave beams is a minimum up to 4 GHz, even during a heavy rainstorm. Beam spreading becomes a problem for microwaves as the transmission distance increases, but systems designed to operate at higher frequencies have the added advantage of operating with smaller transmitting and receiving antennae. Other windows of transmission exist at 35 GHz and 94 GHz. Higher frequencies can alleviate the problem somewhat, but then beam absorption in the atmosphere becomes a problem.

However, in this automotive application, with the distances being on the order of 15 to 100 meters, many of these problems are resolved or non-existent. Thus the choice of power beam at this time would be microwave with laser as a viable option. But in this unique application of wireless power transmission, the primary concern becomes tracking the moving vehicle as it travels on the roadway and the safety of humans and objects in the surroundings.

Hence the safety of operation and the security of the power beam must be unequivocal in all instances for this application. This is the challenge for implementation of the VRC: continuous monitoring of the power beam between the vehicle receiver and the power transmitter. Absolute minimum power beam loss (stray energy) that would trigger an immediate shutdown of the power system with no harm to anyone or anything in the surroundings must be assured.

To date, upwards of 400 kw of microwave energy has been transmitted via wireless power transmission. Order-of-magnitude studies have shown that a vehicle traveling on the highway or a city bus en route can be supplied sufficient energy to maintain a full charge in the vehicle's energy storage unit with power transmitters 1km apart or more [Parise, 2000a]. Therefore, with power transmitters on adjacent poles in city driving, continuous power can be supplied to the vehicle with minimal or even no on-board energy storage. Again this would facilitate the addition of internet access on public transit vehicles.

The effective efficiency of the power beam transmitting system, which would be all-inclusive of system conversions and components, is an estimated 76% for microwave transmission [Brown, 1973]. This would include power line conversion in the power transmitter into a microwave beam, transmission through the atmosphere, reception at the vehicle antenna called a "rectenna", rectenna conversion and electronics, back into the vehicle voltage/current requirements.

The efficiency for laser beam transmission is somewhat less. In recent years this has improved considerably because of the conversion process from electrical power into the required laser beam [Friedman, 1994] and the advent of more powerful lasers [Gover et al, 1995]; and along with beam attenuation in the atmosphere [Hudson, 1969], the overall laser transmission efficiency may approach 30%. However, much of the remaining discussion will focus on microwave energy power beams.

Microwave receivers, called rectennas (receiver + antenna), have been developed to convert the microwave beam back into an electrical current. These devices have been around since the 1960s, and their operation and efficacy are widely known [Dickinson, 1975]. And the devices are rugged enough to withstand automotive applications.

SAFETY

The safety of the power transmission system is an all-important subject that must be considered if this transportation means is to be a serious contender for future use in this country. Pedestrian, edifice, plant and/or animal safety and security around the power beam signal are of prime concern - roasted squab falling from the sky would not be tolerated. Several inherent design features will ensure the safety of vehicle occupants, pedestrians, animals and inanimate objects that will exist daily in and around the VRC locale.

First, the coded and/or encrypted link-up and handshake between the power transmitter and the vehicle will prevent improper usage or erroneous responses of the system.

Second, the location of the translocator signal, in the center of the beam receiver, guides the power beam to the safe, proper location on the vehicle receiver.

Third, the power beam is transmitted only during active, two-way communication between the vehicle and the power transmitter.

Fourth, an optical communication link between the vehicle and the power transmitter will be used. This provides a positive, secure, line-of-sight energy transfer between the power source and the vehicle. This will facilitate monitoring the air space between the vehicle and the power transmitter to ensure power beam shutdown should an object travel in this area when the power beam is activated [Parise, 2000b].

Fifth, and probably the most significant safeguard used by the system, will be that the actual energy transmission will take place in small bursts or packets of energy, and each short burst must be acknowledged as received by the vehicle requesting the energy from the power transmitter before more energy will be sent [Parise, 2001]. Without this two-way handshake for each quantum of energy transmitted, no more power will be sent by the transmitter without a proper relink of communications.

The bursts can be sized so that if a person were struck by one, two or several of these energy packets or bundles, there would be no effect on the person. In this way, an acknowledgement signal from the vehicle for each small burst of energy received must be sent to the Power Transmitting Unit before more energy is transferred.

Several other designated safety and security systems are also being studied. These would include: specific hardware to shut down the power beam if no vehicle were present or if the designated vehicle were not receiving the power beam after a short time; power beam shutdown if damage to the support pole should occur during power transmission; and a means to monitor the region traversed between the power transmitter and the vehicle to ensure no power is sent while an object crosses the normal path of the beam [Parise, 2000b].

EQUATION DEVELOPMENT

Vehicle velocity, pole height, vehicle distance from the pole where the power beam is initiated for charging, etc., are some of the many parameters that must be investigated. Figure 2 shows the coordinate system and variables that are used for the analysis.

The incremental time the traveling vehicle will be in the beam range is

$$dt = dx/v, \qquad (1)$$

where v is the velocity of the vehicle, considered to be constant. The recharge energy or power received on-board during this time is

$$dE_{RC} = P_{beam} \cdot \cos^{n}\alpha \cdot dt, \qquad (2)$$

where P_{beam} is the power beam conversion energy at the rectenna surface if the incident angle, α, was 90°, and n is a cosine law parameter or power.

Typically for microwave power beam energy at the rectenna surface, the value for n is slightly less than 2 [Little, 2000]. Therefore, for the model, 1.8 is chosen.

Combining Equations (1) and (2), and integrating over the distance of power beam influence on the moving vehicle, the amount of energy received on-board is

$$W_{RC} = 2 \cdot [P_{beam} \cdot h^n/v] \int_0^L dx/\{[h^2+x^2]^{n/2}\}, \quad (3)$$

where W_{RC} is the stored energy received by the energy storage unit, L is equidistant either side of the power pole where energy is being transmitted, and h is the vertical height of the Power Transmitting Unit above the vehicle rectenna. The energy consumed, moving the vehicle from L to -L, is

$$W_{drive} = P_{drive} \cdot 2L/v, \quad (4)$$

where P_{drive} is the power needed to move the vehicle on level ground, considered constant. Therefore the net change of energy on-board the vehicle is

$$W_{store} = W_{RC} - W_{drive}. \quad (5)$$

If W_{store} is positive, more energy was stored than needed to move the vehicle from L to -L; if W_{store} is negative, energy was still stored (the amount being W_{RC}), but less than the energy needed to move the vehicle from L to -L. It is preferred that this would always be positive.

The analysis does not consider the additional angle incurred by the energy beam at the rectenna surface due to the distance between the pole mounted on the side of the road and the center of the rectenna located on the traveling vehicle in the roadway. However, this angle is considered negligible and is ignored.

The distance between power transmitting poles is D_{pole}, and the distance between poles when the vehicle is not receiving recharge is $d = D_{pole} - 2 \cdot L$. The energy consumed by the traveling vehicle between power transmitting poles is

$$W_{NoRC} = P_{drive} \cdot d/v. \quad (6)$$

Therefore the total energy consumed by the vehicle as it travels down the roadway is

$$W_{travel} = W_{NoRC} - W_{store}. \quad (7)$$

If the power transmitting poles are placed close enough together, and the energy stored on-board while in the locale of a pole is great enough, the net increase of energy in the energy storage unit precludes the necessity to stop for "refueling". Otherwise "km to empty" ["miles to empty"] can be calculated.

The assumptions for the calculations are obvious: a vehicle traveling at a constant velocity on a level road with no power beam interruptions (pigeons, branches, etc.) and all on-board utility usage (radio, lights, etc.) and power beam signal received on-board (travel through the atmosphere, rectenna conversion, etc.) are constant.

RESULTS

The results of Equations (3) and (4) are shown in Figure 3 for a vehicle traveling at 50km/hr (30mph), and Figure 4 for the vehicle traveling at 100km/hr (~60mph). For the different pole height, h, values above the power consumed curve W_{drive}, there is a net increase of stored energy on board the vehicle; for values below, there is a net decrease of energy in the on-board energy storage reservoir.

When the vehicle is traveling at 50km/hr (30mph), the value used in the model for power consumed, P_{drive} in Equation (4), is 4.8kW. For the vehicle traveling at 100km/hr (~60mph), the amount of power consumed is 17.25kW.

The pole height greatly influences the amount of energy received on-board, especially for the faster traveling vehicle. The influence of the incident angle at which the energy beam strikes the receiver quickly diminishes the amount of energy received at larger distances L. And once the vehicle gets beyond a certain distance L from the pole, there is little energy added to the energy storage unit.

For the 50km/hr (30/hr) traveling vehicle, the obviously longer residence time of the vehicle at the power pole locale allows for a greater amount of energy to be transferred to the energy storage unit, as well as the slower moving vehicle consuming less energy. Therefore shorter distances L and shorter power pole heights can be utilized. Also, the slower moving vehicles would have lower convective heat transfer coefficients off surfaces, allowing for reduced power fluxes at receivers, transient thermal build-up being an assumed concern.

DISCUSSION

The height of the power poles appears to be the strongest influence for the amount of energy that will be received on board the vehicle for the conditions specified. This actually lends itself well to the types of driving conditions normally experienced by drivers in suburban and urban areas.

Crowded suburban and urban road speed limits are typically in the 50km/hr to 70km/hr (30mph to 45mph) range, suitable to a power pole height of 10m to 20m. Normal utility poles are about 12m high. Therefore Power Transmitting Units would be suitable for the existing utility system.

In areas where higher speeds are allowed, typically wider roadways have more wide-open space, and higher power pole heights can be accommodated.

The results also indicate that the small angle between the normal to the rectenna surface and the incident power beam created by the distance from the Power Transmitting Unit located on the side of the road to the vehicle traveling in the roadway can be ignored. At very small values of L, in both figures, energy reduction is diminished slightly. Therefore, for a first approximation, the effect of this angle can be considered negligible.

CONCLUSION

Although power densities at receiver surfaces have yet to be considered, power beam fluxes that have been demonstrated to date can fulfill the energy requirements needed to recharge and/or power a vehicle at typical roadway speeds, as well as for expected topographic constraints along the roadways.

Therefore no extraordinary measures or problems appear to completely eliminate this mode of powering or recharging normal vehicular traffic on our nation's roadways.

Also, methods considered short term on-board energy storage, typically ultracapacitors and flywheels, become much more agreeable to certain driving conditions, especially in daily urban commute traffic, where occasional energy bursts are required.

Therefore, in urban and suburban settings where all electric is desirable (and may one day be a requirement), the VRC can provide the motive power necessary. For vehicles that must travel beyond the recharge grid, hybrid vehicles become desirable.

DEDICATION

The author dedicates his research efforts to his late son Joey Parise, a talented youth whose early passing from this life precluded his chances for fulfilling the dreams of an inquisitive mind, and to those he left behind.

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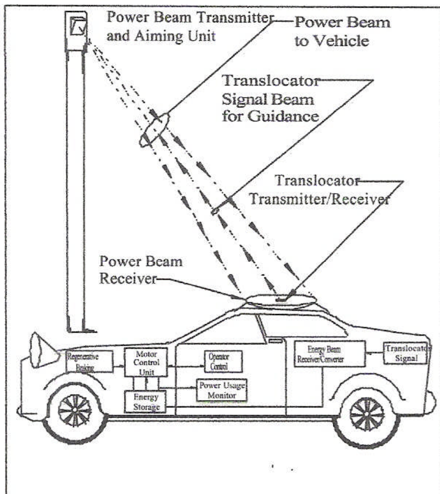

Figure 1: All-Electric Vehicle Components

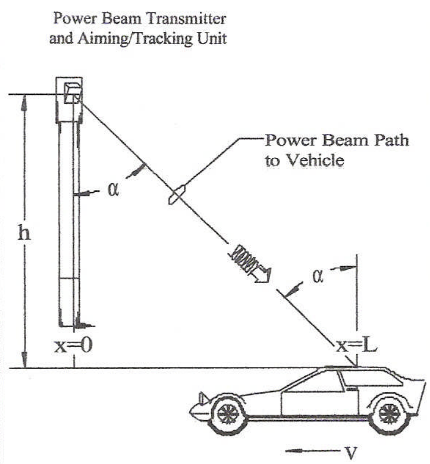

Figure 2: Recharge Model Configuration

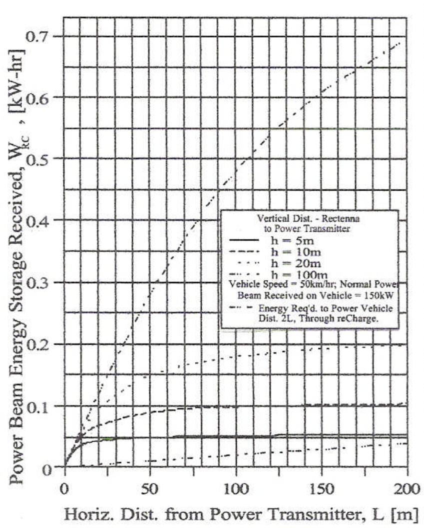

Figure 3: Energy Stored on Vehicle Traveling at 50 km/hr, Accounting for Cosine Law

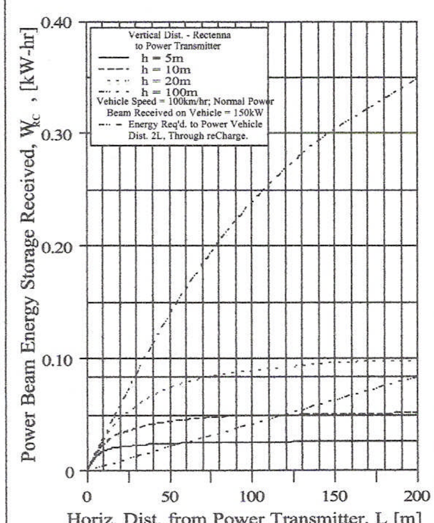

Figure 4: Energy Stored on Vehicle Traveling at 100 km/hr, Accounting for Cosine Law