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CRUISE LANE HIGHWAY CHARGING OF ELECTRIC VEHICLES

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ABSTRACT

The possibility of charging electric vehicles (EV) while they are cruising on highways is explored. Such a technology would break through the 'range anxiety' barrier to mass adoption of EVs. Developments in emerging energy technologies for automotive radar and other applications, have made possible the implementation of wireless millimeter wave beamed power. The rapid advances in the ability to accurately beam and receive power in the 70 to 225 GHz frequency range using solid state components suggests that it will become possible in the near future to beam sufficient power to perform such charging applications. Unlike short-range wireless inductive charging, beamed cruise charging is aimed to work on vehicles traveling as fast as 100 kph on straight segments of the highway, similar to cruise toll lanes used today. Subsequent versions may use aerostats or towers to beam power, enabling power delivery on curved roads in mountainous regions. The paper will survey related prior work and set out preliminary sizing and business case calculations, followed in the final paper by trade studies to perform a first level optimization. We also discuss the architectural requirements, charging rates and perform a sustainability

NOMENCLATURE

BEV Battery Electric Vehicle

ICE Internal Combustion Engine

PHEV Plug in Hybrid Electric Vehicle

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INTRODUCTION

The utility of all-electric automobiles is limited by various factors. The most important one is the 'range anxiety', this is a severe limitation on the adoption rates of battery electric vehicles (BEV). There is a periodic need to stop and re-charge or replace the batteries after traveling a relatively short distance. The long time needed to recharge the depleted battery usually necessitates exchanging the battery for a different one at each charging stop, similar to changing horses on a 19th century Stage Coach. Today three levels of recharging are available. Level 1 is using a home electrical system, taking roughly 8 hours to recharge the batteries after depletion at maximum range. Level 2 is charging from a commercial station, taking about 2 hours. Level 3 is high-current charging, which can complete the charging process in 30 minutes. Even Level 3 compares quite unfavorably to the 5 to 10 minutes needed to refill an automobile gasoline tank. Moreover, charging stations are not widely available outside major urban areas. With the current battery technology, the mass and volume needed to carry enough charge to travel for a few hours at highway speeds, are quite prohibitive. Obviously, these are major obstacles in increasing the market viability of electric automobiles.

The issue addressed in this paper is an approach using emerging technologies to overcome the limitations of a BEV. We address these issues by looking at the feasibility of charging automobiles while they are traveling at highway speeds. If this system is implemented, a BEV's effective range could be increased to match the range of an internal combustion engine (ICE) vehicle. This would imply that BEVs would be suitable for

intercity highway travel, with the assurance of power being available on the go. We developed a model to optimize the number of wireless charging stations required depending on various factors. This model is discussed in detail later in the paper. As seen below, the requirement boils down to delivering roughly 1 kWh per charging station, while the automobile is moving at highway cruise speeds.

MARKET

In order for consumers to adopt BEVs, they must switch from the well established technology of ICE vehicles. For this consumers must appreciate the benefits of BEVs far in excess of the uncertainties involved in adopting the new technology. We expect rational consumers will be indifferent between a ICE vehicle and a BEV with ‘infinite range’. Since our approach to increasing the range of a BEV involves emerging beam power technology, the best way to estimate the market sizing would be a bottoms up approach. In this market estimation approach, the number of vehicles required on the grid is backed out by setting a break even period for the investment. The model is a free cash flow analysis of the investments and revenues earned, to yield the net present value. The number of cars required on the grid is a variable which determines the NPV at the end of a set period. The following are the assumptions on which the computations are modeled.

1. Analysis of Costs and Capital Investment

- (a) An upfront R&D investment of \$2 billion was assumed, but this investment was borne by the federal government and was not accounted for in the NPV analysis.
- (b) The installation of the infrastructure was assumed to be completed in equal phases over a 4 year period. However, the operations would begin on partially completed highways.
- (c) The number of highway miles electrified was assumed to be 400 miles along each major interstate to and from a city.
- (d) Cost per mile of installing overhead high voltage 3 phase cables was taken to be \$250,000 per mile of installation [1]
- (e) The installed equipment was assumed to undergo a straight line depreciation in a 4 year period.

2. Analysis of Revenues

- (a) A price point of 15 cents per kWh was assumed and the total cost per 1000 miles (1600 km) driven was determined from the Figure1.
- (b) Installation of infrastructure completed in phases, hence user base increases with time due to expansion of infrastructure.

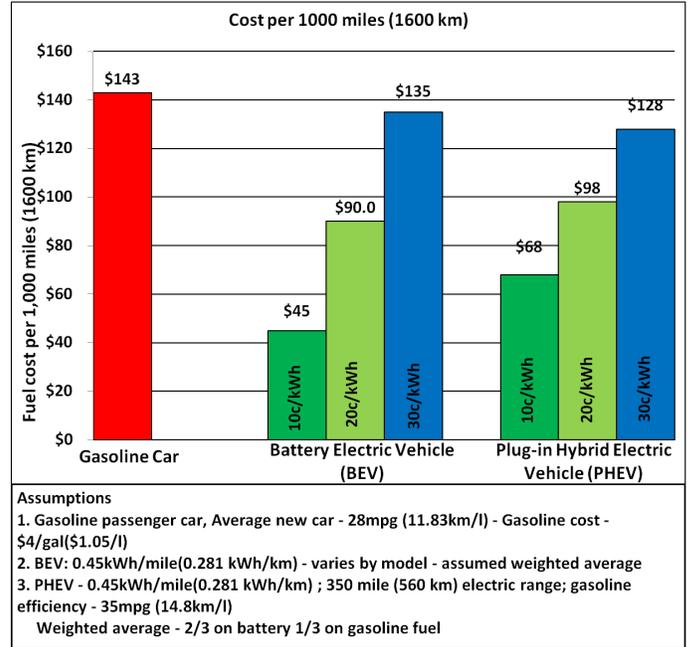


FIGURE 1. COST PER 1000 HIGHWAY MILES (1600KM)

- (c) We assume a cumulative average growth rate of user base as 16% per annum
- (d) The average miles driven per annum was assumed to be 12,000 miles (19,200 km) [2] and 60% highway miles.

Using the net present value(NPV) model and under the assumption of a payback period of 5 years. We determined the number of cars required for this technology implementation to be economically viable. This number along with the NPV variation with time is presented in the Figure2. The NPV model incorporates many variables into the equation to determine the pay back period. A sensitivity analysis was performed to understand the behavior of NPV with changing variables. We chose two variables - the price charged per kWh of electricity and the cost of highway electrification in dollars per mile. It was observed that a small change in the price changed would drastically affect the NPV values at the end of 5 years. The Table 1 summarizes the sensitivity analysis.

ARCHITECTURE

The architecture that we propose consists of a series of charging stations modeled on today’s Express Toll Lanes, where the electric power is delivered by means of millimeter wave beams. The beams are transmitted from antennae places above the highway like today’s highway direction signs. Receivers placed on the automobile hood, roof and trunk will capture the beamed power while approaching and receding from the trans-

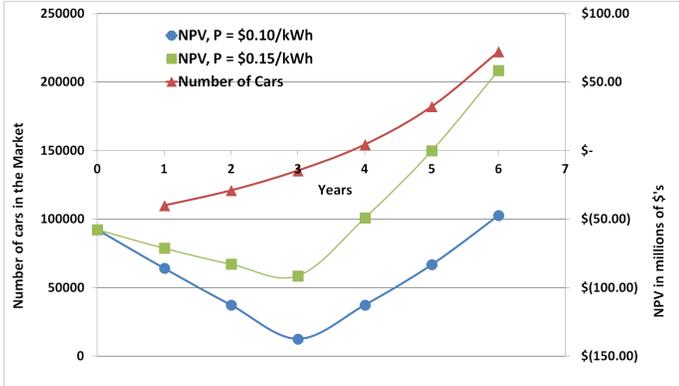


FIGURE 2. NPV BASED ON GROWTH RATE OF NUMBER OF CARS IN THE MARKET

		Price\$		
		0.1	0.15	0.2
Electrification cost(\$/mile)	200,000	-47.94	30.82	109.58
	250,000	-78.76	0	78.76
	200,000	-109.58	-30.82	47.94

TABLE 1. SENSITIVITY ANALYSIS OF NPV (MILLIONS OF \$'s) WITH RESPECTED TO PRICE AND ELECTRIFICATION COST

mitters. Each highway lane at such a charging station will have transmitters sized to lock on to 4 to 5 automobiles at a time, depending on expected traffic density and speed. Charging stations are expected to be set up every 4 to 5 kilometers. Power delivery to these stations may be through usual electric power grid, with converters to the beaming frequency set up at each charging station, or the power may be delivered as millimeter waves through waveguides, for direct feed to the transmitters.

The infrastructure to communicate with vehicles and to conduct financial transactions automatically, is already well-established. Modern cruise lane toll collection is able to assess tolls to fractions of a dollar, based on distance traveled in the toll lanes. To do this, toll systems already connect to cars as they approach, collect information from the vehicle, and inform the system in the vehicle of how much is billed [3]. In the case of the EV cruise charging system, the communication system must also determine whether and how much the vehicle needs charging, the precise position and trajectory of the vehicle and the alignment of the phase array antenna and the vehicle antennae, the hand-off from one antenna to the next as the vehicle approaches, the appropriate power transfer profile. It must monitor the signal return to verify that there is no interruption of the beam, as a safety check. The above description suggests the various issues that

may be expected in most power beaming applications, but also that such applications are close to realization.

Today's constraints on EV charging are battery weight, battery size, cost, charge capacity and temperature limits on maximum charging rate [4]. Our architecture would remove battery weight and size as constraints. However, the temperature limit on charging rate will remain a constraint, and we will add antenna size and beam intensity as new constraints. The primary technological uncertainty in the architecture is the advancement of millimeter wave technology, from today's low-power applications for small devices, to efficient conversion, beaming, reception and reconversion at Megawatt levels.

Prior Work on Wireless Vehicle Charging

There are two US Patents dealing with different aspects of wireless vehicle charging. Charych [5] describes power transfer using ultrasound. Hoelzl et al. [6] describes a wired charging device that uses a wireless communication to convey vehicle and charging parameters. Wireless charging of electric vehicles using inductive chargers cites 30kW levels [7].

Shoki [8] provides a summary Japanese perspective. Power beaming between antennae at two fixed points has been shown since the early 1900s [9], and taken much further using microwaves [10]. Power delivery to UAVs and space vehicles has been studied using microwaves, and more recently, using lasers [11], microwaves [12] and millimeter waves [13].

Requirements Definition

Peak throughput in express lanes has been found to be 1600 cars per hour, but in tight groupings the interval between cars may be down to 0.75 seconds. A brief list of requirements:

1. Assume that charging occurs at highway speed, with no deceleration. A change of lanes may be required if the highway has more than 2 lanes going each way and there is substantial traffic that does not use cruise charging.
2. Beaming can occur to 6 cars in each lane at a given instant, 3 approaching and 3 receding.
3. Automatic lock-on between transmitter and receiver, and handoff between transmitters.
4. Receiver antenna on car has no dimensions larger than 1m.
5. Failsafe beam lock-on ensures that there is no mis-directed beam, and that immediate shutoff occurs when there is any interruption of the beam path except by rain or snowfall.
6. Power level sized for twice the level needed on a clear day, to accommodate losses due to rain, beyond what can be compensated by slower highway speeds.
7. Facility is automatic and available 24 hours a day, every day.
8. Financial transactions for charging are automatic, similar to present highway tolling.

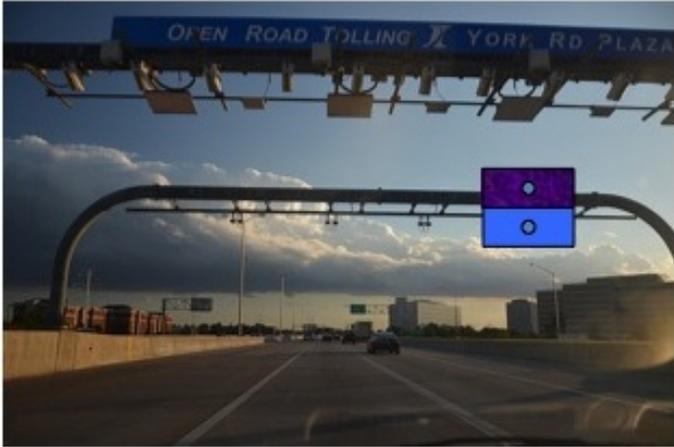


FIGURE 3. A CAR APPROACHING A HIGHWAY CHARGING STATION

9. Spatial frequency of charging stations is sufficient to compensate for the energy consumed in traveling between charging stations.
10. Batteries assumed to be kept in optimal charge level for best charging.

Proposed Baseline System

Let us consider a conceptual architecture for such charging, modeled on wireless toll lanes that have appeared in several US states, where frames set up over highway lanes exchange signals with windshield-mounted modules, conducting financial transactions at highway speeds and acquiring high-resolution images if needed. The charging station adds millimeter wave antennae facing in both directions, beaming power to a forward-facing antenna as the vehicle approaches over a distance of 500 meters, and to a rearward-facing antenna as it recedes for 500 meters. Phase array technology will minimize antenna motion. Several independent antennae can operate from one array, which could be integrated with information signboards so that a 220 GHz transmitter has an effective diameter of 5 meters. The needed charging rate rises with vehicle speed at the rate of 2.5kW per kmph of speed. Thus charging while driving at 110 kph requires a charging rate of 275 kW, for the 18 seconds of charging time available, implying a millimeter wave intensity of nearly 400 kW/m². These are for a 5-mile (8km) spacing between charging stations, and come down in direct proportion to the spacing. Buses and trucks would move slower through special charging lanes. Peak throughput in express lanes has been found to be 1600 cars per hour [14], but in tight groupings the interval between cars may be down to 0.75 seconds.

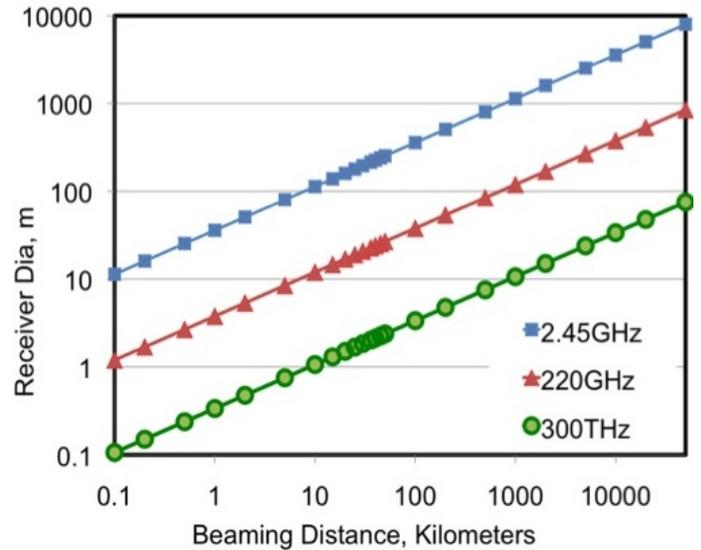


FIGURE 4. ANTENNA SIZE VS. BEAMING DISTANCE FOR DIFFERENT FREQUENCIES

DISCUSSION: TECHNOLOGY READINESS AND VARIATIONS

Millimeter Wave Technology

The elephant in the room, figuratively speaking, is the technology of millimeter wave power generation, beaming, and conversion. Today it is not possible to immediately build an efficient, lightweight converter to or from 220 GHz. Also, solutions for the high loss in rain and snow at low altitudes, must be sought. On the other hand, driving in rain or snow usually requires slowing down for safe travel, so that the beaming could occur over a shorter range in those conditions. Heavy rain and snowfall tends to be localized, so that only a few charging stations may be affected at any given time.

Developments towards using millimeter wave retail beaming are surveyed by Komerath et al [15]. The rapid advances in 77 GHz radar, where some designs are based on 220GHz components, indicates promise. The mass needed per unit power is far less of a concern in this ground-based application than it is in applications based on Space or Lighter-Than-Air platforms. This means that converters based on solid state components can be used here long before their mass is reduced and efficiency improved sufficiently to be used in Space applications. End-to-end efficiencies approaching 70 percent are already feasible, we believe, using 220 GHz beaming, for the phases of conversion to, beaming and conversion from 220 GHz, given the short distances of beaming. Thus we anticipate that applications such as Cruise Charging will become drivers of this technology.

Atmospheric transmission of millimeter waves is an issue that requires much more study. Transmittance data vary de-

pending on the data collection sites and atmospheric conditions [16,17]. Beams of wavelengths 2.14mm (140GHz) and 1.43 mm (210GHz), respectively, have very high transmittance at the dry and polar conditions. So 140 and 210 GHz would be of interest for power beaming applications and 210 GHz would be preferable because it will lead to smaller receiver size. Although transmittance at 220GHz is less than that at 210 GHz according to these data, the choice of 220 and 223 GHz made in several military systems suggests other advantages. Horizontal propagation of millimeter waves is costly at low altitudes, as there are substantial losses. In the cruise charge application we believe these losses are acceptable since the beaming distance is less than 1 kilometer, and the higher price charged to account for these losses is justified by the convenience of highway-speed charging.

Vehicle to Grid (V2G)

Studies show that 92 percent of vehicles are actually parked during the times of peak electricity demand. Beaming power from a parked vehicle to a grid-connected or stand-alone receiver has been considered as a means to alleviate rolling blackouts or demand peaks, serve as spinning reserves, or provide regulation services, the last being found to be the most promising application. Once power beaming to vehicles is available, the vehicle antenna can serve as the means for sending emergency power to communities where the main power grid is downed by natural disasters, or indeed to alleviate stress on the wired grid during peak times .

Aerostats for EV charging

Tethered aerostats could reduce the power level needed, since they can keep a roof-mounted antenna in sight for a much longer distance and through curves and gradients in the road. In this application the aerostat antenna would be held at 500 meters to 1 km above the ground. The tether would take electric power up to converters on the aerostat, or actually have millimeter waveguides inside the tethers. Aerostats can offer enough downward-pointing transmitter area to enable a roof-mounted vehicle antenna to be quite compact and aerodynamic. This might also motivate manufacturers to integrate a PV panel with the millimeter wave roof antenna, to generate enough solar power to run a ventilator while the vehicle is parked. Many stretches of highways could be quickly served by putting up aerostats as demand rises. Power could be passed from one aerostat to another efficiently by parking them at 5km altitudes, with the down-beaming antenna suspended at a low altitude. Thus such a charging infrastructure can be put in place very quickly, even over mountainous areas.

CONCLUSIONS

1. Cruise charging can have a revolutionary impact on the practicality and therefore market appeal of EVs.
2. Considered what can be done with Millimeter Wave beaming to enable cruise charging
3. Identified parameter ranges for the business case to be positive.
4. Presented a baseline case, that appears to be technically feasible.

Further refinements to be presented in the final paper.

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