Design of On-Line Electric Vehicle (OLEV)

N.P. Suh, D.H. Cho, and C.T. Rim

Abstract To minimize the greenhouse effect caused by emission of CO_2, many automobile manufacturers are developing battery-powered automobiles that typically use re-chargeable lithium polymer (or ion) batteries. However, the future of these battery-powered electric cars is less than certain. The re-chargeable lithium batteries are heavy and expensive with a limited life. Furthermore, Earth has only about 10 million tons of lithium, enough to put one battery system in each vehicle in use today worldwide. This chapter presents a new design concept for an alternate electric car – On-Line Electric Vehicle (OLEV). OLEV draws its electric power from underground electric coils without using any mechanical contact. The maximim efficiency of power transmission over a distance of 17 cm is 72%. OLEV has a small battery, which enables the vehicle to travel on roads without the underground electric coil. Batteries are recharged whenever OLEV draws electric power from the underground coils and thus, do not require expensive separate charging stations. The infrastructure cost of installing and maintaining OLEV is less than those required for other versions of electric vehicles. This chapter presents the overall design concept of OLEV.

Keywords Axiomatic design · Electric car · Wireless power transmission · Automobile · System design

1 Introduction

This paper[1] presents the overall design concept of a new electric vehicle being developed at KAIST.[2] The all-electric car of KAIST, named the On-Line Electric Vehicle (OLEV), acquires the electricity from underground coils via wireless transmission of electric power. This innovative technology addresses three major problems: Korea's energy infrastructure that depends on imported petroleum, the poor quality of air in large cities, and the global warming caused by greenhouse gases.

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the ambient temperature of the earth may rise by more than 2°C relative to the pre-industrial level unless the average CO_2 concentration of the earth's atmosphere is reduced by 50% and that of the industrialized nations by close to 100% [1]. If the temperature rise is unchecked, we may invite many adverse ecological consequences such as heat waves, drought, tropical cyclones, and extreme tides. To prevent such ecological calamity, many nations are now imposing limits on greenhouse gas emission.

Historically major new technological advances have become the engine for economic growth. With economic growth, the use of energy has also increased. Since the primary source of energy has been fossil fuels, the concentration of greenhouse gases in the atmosphere, especially CO_2, has increased. Today, the United States and China are two of the major emitters of CO_2 on per capita basis, while on GDP basis, Russia and China are the leading CO_2 generators. International Energy Agency [2] clearly states that the current energy trend is not sustainable environmentally, economically and socially. Therefore, we must devise solutions to achieve the future economic growth without adverse environmental effects.

There are some 800 million automobiles with internal combustion (IC) engines in use today worldwide. These automobiles are a major source of greenhouse gases, especially CO_2. Thus, an effective way of dealing with the global warming problem is to replace IC engine-powered automobiles with all electric vehicles. The use of electric cars will also improve the quality of air around major cities.

To replace IC engines, many automobile companies are developing "plug-in" electric cars, which use lithium ion (or polymer) batteries that can be recharged at home or at

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[2] Acronym for Korea Advanced Institute of Science and Technology.

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charging stations. However, the basic premise for plug-in electric cars raises many questions. First, the cost of lithium batteries is high. Second, the batteries are heavy. Third, the charging time for the battery is so long that it requires an expensive infrastructure for charging stations. Finally, perhaps the most important of all, is the finite supply of lithium on Earth. Earth has only about ten million tons of lithium that can be mined economically, which is enough for about 800 million cars, almost the same as the number of cars in use today.

The KAIST On-Line Electric Vehicle (OLEV[3]) draws its electric power from underground coils without any mechanical contact [3]. OLEV cars and buses have a small auxiliary battery to propel the vehicle on roads without the underground coil. The battery is also used when extra power is needed. In 2009, we installed underground coil systems on the KAIST campus and built an OLEV bus and an OLEV SUV, which are used for design verification. The maximum efficiency of electric power transfer of the OLEV systems is 72%. We are planning to install an experimental bus line in Seoul, the capital city of Korea in 2009, and other cities in 2010.

This paper describes the overall concept of the OLEV system. The details of the design will appear in future publications.

2 Functional Requirements (FRs) and Design Parameters (DPs) of the On-Line Electric Vehicle (OLEV)

2.1 FRs, DPs, and Constraints of OLEV

The performance of OLEV is expected to be approximately the same as vehicles with IC engines. The highest-level functional requirements (FRs) of OLEV are as follows [4, 5]:

FR1 = Propel the vehicle with electric power
FR2 = Transfer electricity from underground electric cable to the vehicle
FR3 = Steer the vehicle
FR4 = Brake the vehicle
FR5 = Reverse the direction of motion
FR6 = Change the vehicle speed
FR7 = Provide the electric power when there is no external electric power supply
FR8 = Supply electric power to the underground cable

Constraints are as follows:

C1 = Safety regulations governing electric systems
C2 = Price of OLEV (should be competitive with cars with IC engines)
C3 = No emission of greenhouse gases
C4 = Long-term durability and reliability of the system
C5 = Vehicle regulations for space clearance between the road and the bottom of the vehicle

The design parameters (DPs) of OLEV may be chosen as follows:

DP1 = Electric motor
DP2 = Underground coil
DP3 = Conventional steering system
DP4 = Conventional braking system
DP5 = Electric polarity
DP6 = Motor drive
DP7 = Re-chargeable battery
DP8 = Electric power supply system

2.2 The Second Level FRs, and DPs

The first-level FRs and DPs given in the preceding section must be decomposed until the design is completed with all the details required for full implementation.

The second-level FRs are the FRs for the highest-level DPs and at the same time, the children FRs of the first-level FRs [4, 5]. For example, FR1 can be decomposed to lower-level FRs, e.g., FR11, FR12, etc, which are FRs for DP1. Then DP11 can be selected to satisfy FR11, etc. These lower-level FRs and DPs provide further details of the design. There are many patents pending, which describe the details of the OLEV system, including the lower-level FRs and DPs [3].

2.3 Design Matrix (DM)

Design Matrix (DM) relates the FR vector, {FRs}, to the DP vector, {DPs}, which can be formulated after DPs are selected to satisfy the FRs. DM is used to check if there is any coupling of FRs caused by the specific DPs selected for the design. According to the Independence Axiom, FRs must be independent of each other.

An integration team of the OLEV project constructed the DM for the OLEV system to identify and eliminate coupling between the FRs at several levels. The final design was either uncoupled or decoupled designs. When there was coupling, its effect was minimized by making the magnitude of

[3] Patents pending. Trade mark OLEV is also pending.

the element of the design matrix that caused coupling much smaller than other elements through design changes.

2.4 Modelling of the FRs and DPs

A given FR may have several different DPs. In this case, the final DPs were selected through modelling and simulation of the design using different DPs. The final values of DPs were also determined through modelling and simulations before the hardware was actually built.

3 Physical Embodiment

3.1 OLEV Bus

Figure 1 shows the OLEV bus built on the KAIST campus. KAIST and collaborating industrial firms converted a conventional bus with an IC engine to an OLEV bus. We attached power-receiving units to the bottom of the bus, which picked up the power transmitted from the underground coil. The distance between the underground coil and the power-receiving unit on the bus was about 17 cm. The maximum electric power transfer efficiency was 72%, which exceeded our design goal of 60% (See Fig. 2). With the reduction of the distance between the pick-up unit and the underground coil, the efficiency increases.

The OLEV bus is designed to draw 60 kW of electric power. When it needs more power for acceleration, etc., it draws additional power from the battery, which is recharged when the motor does not need the peak power.

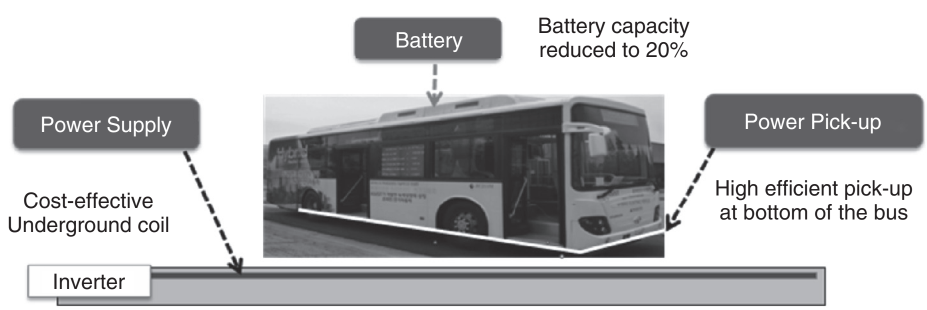
3.2 Underground Electric Coil

The design of the underground coils is one of the most important parts of the OLEV system. We have designed many different versions.

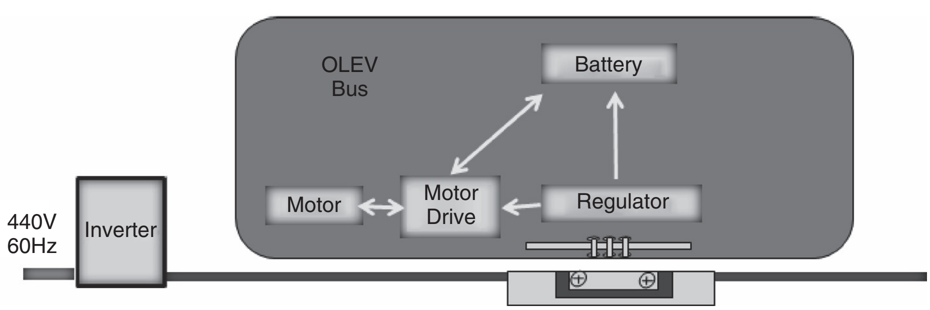
The underground electric power coils do not need to be installed everywhere because the small battery on board can supply the power when the electric power from the underground coil is unavailable. The distance the vehicle has to travel without getting the power from the underground coil determines the battery size. Our current design goal is to install a battery that can give free driving ranges of 10 km for a bus and 30 km for a car.

According to our analysis, if about 30% of the roads in Seoul have the underground electric power coil, most vehicles will be able to drive around the city without recharging the battery off-line.

In the case of OLEV buses that follow pre-determined routes, the underground electric power line will be installed at the bus stations, intersections with stoplights, and only



(a) OLEV Bus



(b) Block diagram of OLEV

Fig. 1 OLEV bus and block diagram. (**a**) OLEV bus and (**b**) Block diagram of OLEV

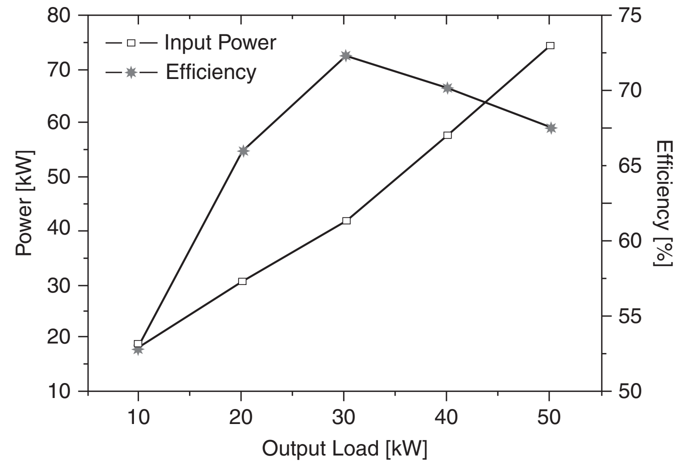


Fig. 2 The power and efficiency of the OLEV

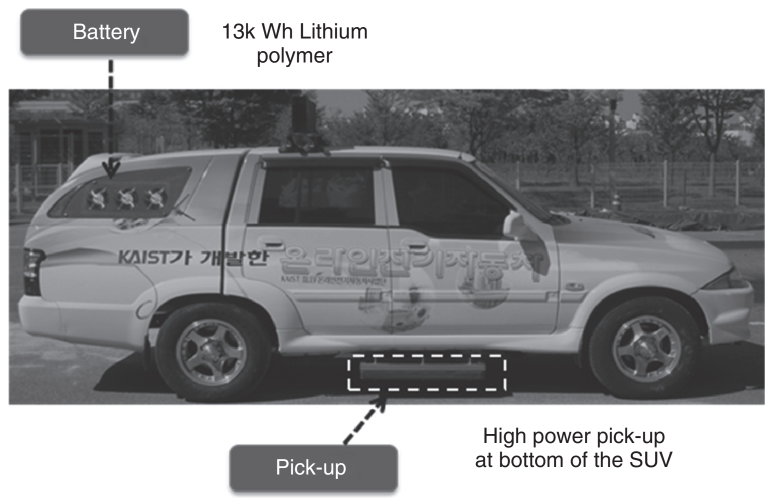


Fig. 3 High powered OLEV SUV

critical segments of the road. While the bus is at a station to discharge passengers and pick up new passengers, the battery is recharged so that the OLEV bus can reach the next bus station with the battery power.

3.3 OLEV SUV

We also built an OLEV sports utility vehicle (SUV). It also had a power pick-up unit attached to the bottom of the vehicle and a set of batteries for free travel when the underground power line is absent. The OLEV SUV is designed to draw about 20 kW of power. (See Fig. 3).

3.4 Cost of the OLEV System

We compared the infrastructure cost of OLEV versus many other electric vehicle systems, which is shown in Fig. 4. The infrastructure cost of OLEV is only about 73% of that of

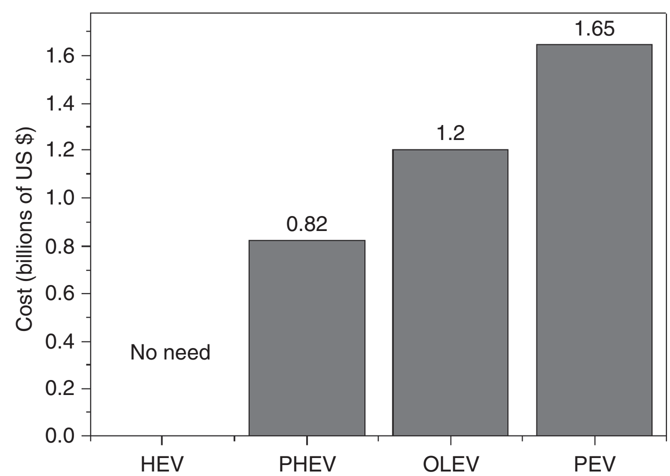


Fig. 4 Comparison of the cost for infrastructure for PEV (plug-in all battery electric vehicle), OLEV, PHEV (plug-in hybrid electric vehicle), and HEV (hybrid electric vehicle with IC engine). Assumtion: The infrastructure is constructed in Seoul, Korea

Table 1 Energy consumption costs (Driving distance: 13,286 km per year)

Type	Energy consumption per year			Total energy cost	Reduced energy cost
	Gasoline (L)	LPG (L)	Electric (kWh)	($/year)	($/year)
Gasoline	874			1,254	–
OLEV			4,429	391	863
HEV	624			895	360
HEV (LPG)		746		639	616
PHEV	312		1,536	568	686
PEV			3,126	276	979

all battery driven systems. Its cost also compares favourably with electric track-trolley system by a greater margin.

As shown in Table 1, the operating cost of OLEV, which is primarily the electricity cost, is estimated to be only 31% of cars that use gasoline.

The manufacturing cost of OLEV passenger vehicles should be less than that of the hybrid cars and even regular cars with IC engines when they are produced in economical lot sizes.

3.5 Electromagnetic Field (EMF)

Whenever electrical devices are used, including coffee maker at home, electromagnetic fields are emitted. The allowable level of EMF depends on the frequency of the electromagnetic field.

We have made extensive measurements of the electromagnetic field, including the regions around the underground power line, between the OLEV vehicle and the underground power lines, and inside the vehicle.

Near the platform where passengers wait for the OLEV, it is in the range of a few tens of mG, which is well within the allowable limit. Inside the OLEV bus, the EMF level is negligible, being in the range of 1–20 mG depending on the position. Between the area right below the vehicle and the road, which is not accessible to passengers, the EMF level may exceed the allowed level, but people cannot normally get into this confined space.

4 Discussion: Future Prospect

4.1 Energy and Environment

Two basic reasons for developing OLEV buses and cars are for better air quality in large cities and the reduction of CO_2 in the earth's atmosphere to slow global warming. If we remove cars with IC engines from the streets of major cities, the quality of air will improve. However, the total reduction of greenhouse gases depends on the specific means of electricity generation, which may change more gradually. The use of OLEV may not affect the world's primary energy demand in the short term.

According to [2], the world energy use will grow at the rate of 1.6% per year on average in 2006–2030 from 11,730 MTOE[4] to 17,000 MTOE, an increase of 45%, non-OECD countries accounting for 87% of the increase. About a half of the overall increase will be because of the economic growth of China and India. The energy consumption by non-OECD countries exceeded that of the OECD in 2005. Global demand for natural gas grows more quickly, by 1.8% per year, its share in total energy demand rising to 22%. World's demand for coal increases by 2% a year on average, its share in global energy demand climbing from 26% in 2006 to 29% in 2030, which is a major generator of CO_2. The use of nuclear power will decrease from 6 to 5% relative to the increased use of energy, although the number of nuclear power plants will increase in all regions except some European OECD countries. Modern renewable technologies are growing rapidly, overtaking gas to become the second-largest source of electricity, behind coal, soon after 2010 [2].

4.2 OLEV and Supply of Electricity

To replace all IC engine cars being used in Korea in 2009 with OLEV cars, Korea needs to dedicate two nuclear power plants for electricity generation. At this time, Korea produces about 40% of its electricity using nuclear power plants. It is building eight more nuclear power plants. The cost of electricity is only 22.7% of fossil fuel in Korea.

Many countries in the world do not have any oil. These countries will have to rely on nuclear power if they are to

[4] Million Tons of Oil Equivalent.

replace all IC engine driven cars with OLEV cars and buses, without causing global warming.

To reduce the emission of CO_2, we must use more nuclear power plants and renewable energies to generate electricity. In Denmark, windmills produce about 20% of the electricity used in the country. Until we develop other green technologies for generating electric power, many countries will have to rely on nuclear power during the next 50 years. Countries like Korea are not best situated to make use of renewable energy sources. According to the International Energy Commission, the nations around the world need to build 1750 new nuclear power plants until 2050 to meet the energy needs of the world, about 35 new plants a year.

4.3 OLEV vs. Plug-In all Battery Cars

The developers of plug-in all battery cars are banking on low-cost light-weight batteries. However, there is a fundamental limit to the reduction of size and weight of any battery, because batteries need physical structures and space that do not contribute to electric power generation. Furthermore, the total known deposit of lithium is only 10 million tons. Although there is lithium in seawater, the cost of removing them will be prohibitive unless a new low-cost technology is developed.

Although these all battery cars have advantages over OLEV in the regions where the population density is so spares that the cost of laying underground coils for OLEV cannot be justified, they require many charging stations which may add significant cost. In these regions, cars with IC engines may be the best alternative.

There are many significant problems associated with implementing the all-battery plug-in car system, which include the long charging time, the high power capacity needed at charging stations, and the reduced efficiency with increase in the charging rate.

4.4 Safety

To be sure that there is no question at all about the perceived safety of OLEV, we have designed our system so that people are minimally exposed to EMF within the allowable limits. Where the exposure to the electric field is unavoidable, the magnitude of EMF is controlled to be well below the allowable level. A segmented power supply system for OLEV and specially designed coils will further reduce the EMF level to enhance safety.

4.5 Economic Competitiveness

Based on extensive analyses done, we are confident that OLEV will be much more economical than plug-in cars.

5 Summary

The On-Line Electric Vehicle (OLEV) being developed at KAIST shows promise. We have installed underground electric power coils underneath asphalt road and built an OLEV bus and an OLEV SUV to demonstrate the viability of the basic concept. We transferred electric power over a large distance from underground coils to OLEV. The system operates with sufficient transfer of power even when OLEV is not exactly on top of the underground coils.

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