Road Embedded Wireless Charging for Public Transit and Commercial Fleet Battery Electric Vehicles

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Abstract

Clean public transit and heavy duty commercial fleets in the 21st century need to eliminate carbon emissions, reduce air pollutants, and support energy independence without compromising fleet operator's need to reduce rising operating costs and comply to continuous regulatory and public policy pressure to implement a green transport solution. To date, commercial adoption of battery electric vehicles (BEV) for public transit and heavy duty commercial fleets has been challenged by issues associated with the battery including: price, weight, volume, driving range, and the charging infrastructure. The Online Electric Vehicle (OLEV™) system technology enables battery electric vehicles to overcome the EV battery challenge by reducing on-board battery size as much as 80 per cent and utilizing an inductive charging system that transfers electric power wirelessly from the road surface while the vehicle is in stationary or "in-motion" mode. The OLEV wireless charging system uses patent-pending Shaped Magnetic Field in Resonance (SMFIR™) technology to support the efficient transfer of wireless power over a large air gap that is powerful enough to support the operations of heavy-duty public transit and commercial fleet applications. With the ability to replenish its energy level continuously from a road infrastructure, there is no limit on driving range, no need to pull a vehicle out of service periodically for recharging the battery. A significantly smaller battery also means the vehicle is lighter, easier to maintain and more efficient. Eliminating the need to wait on technological advances, the OLEV system is ready for adoption using an economically viable business model from an environmental, energy cost savings, and, total investment perspective.

Keywords: commercial, electricity, fleet, inductive charger, ZEV (zero emission vehicle)

1 Introduction

The mass adoption of battery electric vehicles has lagged behind due to technological issues associated with the battery including: price, weight, volume, driving range, charging time and efficient charging infrastructure.

Online Electric Vehicle (OLEV™) technology solves these electric vehicle (EV) battery challenges. The OLEV system allows battery electric vehicles to continuously operate with no limit on driving range while utilizing a much smaller size battery. There is no need to pull the vehicle out of service for recharging the battery since the vehicle is recharged as needed in both dynamic ("in-motion") and stationary charging mode while the vehicle is operating on the route.

The essence of an OLEV system is to minimize the size of the battery by reducing the dependency on stored energy to power an electric vehicle, which is achieved by replenishing the energy level of the on-board electric vehicle battery as needed from a road embedded charging infrastructure.

The OLEV system uses patent-pending Shaped Magnetic Field in Resonance (SMFIR™) technology to support the efficient transfer of wireless power over a large air gap that is powerful enough to support the operations of heavy-duty public transit and commercial fleet applications.

Key target market segments that can benefit from the OLEV road embedded charging system include:

- Bus Rapid Transit (BRT) systems
- City and municipal bus lines
- Airports and seaports
- Campuses and parks
- Commercial delivery fleet
- Industrial heavy duty vehicles

The OLEV technology has been demonstrated to be safe to human from its electromagnetic field (EMF) and electromagnetic interference (EMI) level.

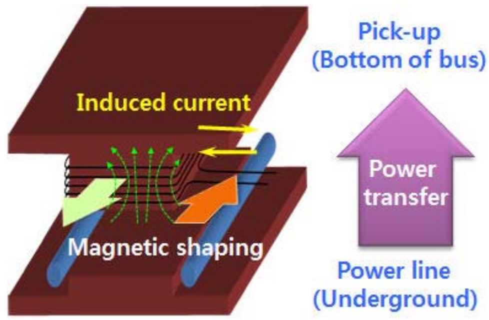
By optimal placement of road embedded charging pads and power tracks on the route based on route characteristics and operating service level requirements, the OLEV system can offer an economically attractive, zero emission transportation solution for many public transit routes with fast recovery of initial capital expense through recurring cost savings of fleet operating expenses. As of this writing a limited number of commercial and pilot deployments of OLEV system exist for public transit buses and an OLEV Tram for a theme park in South Korea.

2 Shaped Magnetic Field in Resonance (SMFIR™) Technology

To power an electric motor on an OLEV-equipped vehicle, the vehicle relies on a small on-board battery and a wireless charging system using Shaped Magnetic Field in Resonance (SMFIR™) technology. The SMFIR technology transfers electric power wirelessly, safely, and efficiently from road embedded charging pads or power tracks, the “electric road”, to the vehicle while the vehicle is “in-motion” (dynamic) or stationary. To efficiently transfer electrical energy through an open air gap, the SMFIR technology focuses the magnetic flux generated by the road infrastructure. This flux is gathered by pickup modules on the OLEV-equipped vehicle and transformed to DC power to charge the battery or supplement the drive to the vehicle motor. The road power track receives its energy from an OLEV roadside inverter through the local electrical power grid.

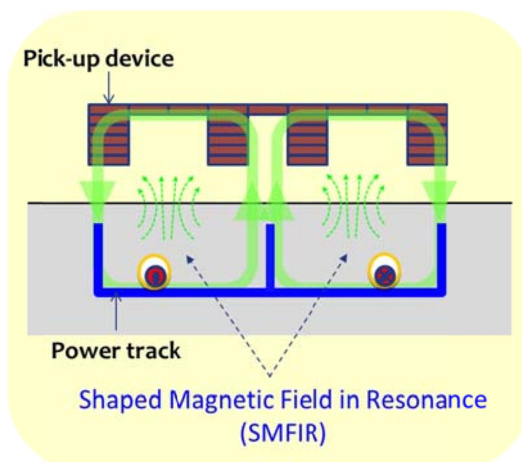
The SMFIR technology has two key components: the charging pad or power track embedded in the roadway and a pickup module on the vehicle. Figure 1 shows the vertical magnetic flux of the power lines and pickup module.

Figure 1: Schematic of SMFIR wireless power transfer technology



The power tracks (roadway infrastructure) are constructed of two power conductors with opposite current directions forming a current loop (see Figure 2).

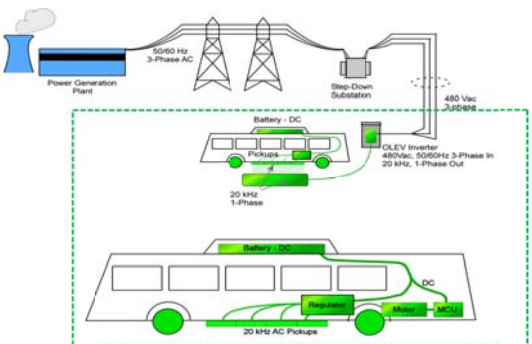
Figure 2: Schematic of opposite current directions forming a current loop



This electrical current induces a magnetic flux around each of the power lines, which is shaped to reach the vehicle, using the magnetic poles in the power track. The pickup module design includes cooper coils around a ferrite core, which picks up the vertical magnetic flux. To maximize the power transfer, the pickup mounted under the vehicle is tuned to the frequency of the magnetic field generated by the power tracks. The design of the magnetic field is the key technology to maximize the electrical performance: power transfer capacity, transfer efficiency, and the electromagnetic field (EMF) level.

To operate an OLEV-equipped vehicle, the power transfer capability of the SMFIR technology determines the maximum power that can be transferred from the power tracks embedded in the road to the pickup module in the vehicle, which consequently determines the maximum recharge rate and time. The entire grid to vehicle power transfer path is shown below (see Figure 3).

Figure 3: Power Flow Schematic



A roadside power inverter may supply power to multiple charging pads or power tracks.

3 Safety of the OLEV System

The wireless charging technology utilized by an OLEV-equipped vehicle is demonstrated to be safe. Vehicles using the OLEV system are pure electric, and the usual safety precautions for batteries are required. In addition, the use of SMFIR technology to wirelessly power the vehicle generates EMF radiation. An OLEV-equipped vehicle meets all international standards for electromagnetic field (EMF) radiation. The OLEV system has been tested and validated and exceeds all safety requirements designated by the ICNIRP in Europe and IEEE in the U.S. (see Table 1).

Table 1: International Standards for Electromagnetic Field (EMF) Exposure Limits

Public Exposure Threshold mG (milli Gauss)	Country/ Group	OLEV Vehicle
62.5 mG	S. Korea/KRISS	✓
200 mG	Europe/ICNIRP	✓
2000 mG	US/IEEE	✓

Based on the international standards for the electromagnetic field (EMF) exposure limits, the EMF radiation measured for an OLEV system equipped electric vehicle is well below the internationally specified level of 62.5 mG at 20 kHz. For comparison, the earth's magnetic field strength is approximately ten times greater than 62.5 mG (see Table 2).

Table 2: Comparison of Electromagnetic Field (EMF) Exposure Levels

Object	Strength of EMF mG
OLEV-equipped vehicle	< 62.5 mG
Strong refrigerator magnet	~ 100 G
Earth's magnetic field	450 mG

There have been no effects observed on human heart pace makers and other electronic devices from proximity testing of the electromagnetic interference (EMI) from an OLEV system equipped electric vehicle.

4 Core Target Markets for OLEV

While the OLEV technology is applicable to all land transportation systems, there are two key elements: Gross Vehicle Weight (GVW) and Route Characteristics that are most relevant in determining the economic viability of the OLEV system compared to other alternative fuel types for public transit such as clean diesel, compressed natural gas (CNG), plug-in hybrids, or fuel cell vehicles.

The OLEV technology is particularly well suited for public transit and/or commercial fleet applications where heavy-duty vehicles operate on a well-defined (e.g., fixed or semi-fixed routes such as bus routes, airport terminal routes, campuses or commercial delivery routes) route repetitively while logging a large, predictable driving mileage per day.

Fleet operations that are particularly attractive candidates to deploy an OLEV-equipped electric vehicle include:

- Public transit routes such as Bus Rapid Transit (BRT) and city bus lines
- Airport terminals, rental car fleets
- Seaport trucks and freight vehicles
- Amusement and theme parks
- Public and private commercial fleets
- Campuses

Bus Rapid Transit (BRT) systems are particularly suitable to adopt the OLEV technology in that the right of way is already in place and heavy traffic of inner city advanced bus systems can save substantial fleet operating expenses over time, not to mention the benefits of clean, emission free transportation. Similarly shuttle services at airports and campuses as well as commercial fleet vehicles operated by public and/or private sectors that service delivery routes, particularly in an urban environment can benefit from the deployment of OLEV equipped electric vehicles.

OLEV technology can be retrofitted to existing fleets or deployed in all new fleets. It is also an alternative to replace catenary-based electric trolleys and light rail systems owing to significant cost savings on the infrastructure deployment and on-going maintenance, less safety concerns and pure aesthetics.

5 Value Proposition and Benefits of the OLEV System

The OLEV system delivers on the three key performance indicators for the electrical vehicle market: Cost (energy and battery), Safety (environment and convenience), and Range (service level). Electric vehicle solutions that maximize on all three of these factors deliver the best value proposition for the market.

5.1 EV Battery Size and Cost Savings

To date, mass adoption of electric vehicles has lagged behind due to technological issues associated with the battery including: price, weight, volume, driving range, and the charging infrastructure. One of the major benefits of the OLEV system is that the technology enables electric vehicles to overcome battery technology limitations and cost by reducing on-board battery capacity requirement by as much as 80 per cent since the road embedded wireless charging infrastructure recharges the on-board battery while the vehicle is in operation. Smaller size battery not only saves the initial vehicle cost and on-going battery maintenance expenses but also reduces overall vehicle weight substantially.

5.2 CO2 Emission Reductions

The OLEV system is designed to power electric vehicles, and this eliminates the need to use an internal combustion engine. By not utilizing an internal combustion engine, the level of CO2 and other emissions from the tailpipe of the vehicle are significantly reduced or eliminated.

Table 3: CO2 Emission Reduction Comparison

Heavy Duty Vehicle (fuel type)	Annual CO2 Emission (tons)	Annual CO2 Reduction (tons)	Savings (%)
Diesel	132	-	-
Diesel Hybrid	98	34	26
BEV	0*	132	100
OLEV	0*	132	100

Comparison based on the following assumptions:
Annual bus miles: 50,000
*Tail-pipe emission only

5.3 Operating Cost Savings

An OLEV-equipped electric vehicle delivers significant fuel cost savings benchmarked against a heavy-duty diesel vehicle. When compared to a diesel heavy-duty truck, an OLEV vehicle delivers a 79% fuel cost savings (see Table 4).

Table 4: Annual Fuel Cost Comparison

Heavy Duty Vehicle (fuel type)	Annual Fuel Costs ($)	Annual Savings ($)	Savings (%)
Diesel	51,813	-	-
Diesel Hybrid	43,668	8,145	16
BEV	11,000	40,183	79
OLEV	11,000	40,183	79

Comparison based on the following assumptions:
Annual bus miles: 50,000
Fuel cost: $4.00 per diesel gallon and $0.10 per kWh

5.4 Unlimited Range (Service Level and Performance)

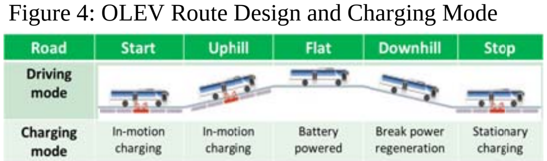
An OLEV-equipped vehicle can provide unlimited driving range even with a small battery and eliminate the need to remove the vehicle for recharging the battery. To provide the highest level of service and performance, a route is designed with the most efficient and optimized charging infrastructure to ensure maximum performance.

To operate an OLEV-equipped vehicle, typically, a power track needs to be installed when the required driving power exceeds the battery power discharge capacity. Therefore, the route requires a combination of stationary charging pads and “in-motion” (dynamic) power tracks to balance energy consumption for the route. Upon route evaluation, the length and location of the power tracks for dynamic charging can be determined. In general, the system is designed to have the same amount of energy consumed on each pass of the route and the state of charge (SOC) of the battery to remain within certain parameters en-route. By power being replenished through stationary and "in-motion" (dynamic) recharging en-route, the SOC level remains unchanged after the completion of the entire route. Typically, a small portion of the road is only required to be electrified. A route designed with enough aggregate dwell time, will require a minimal amount of dynamic charging, if none, since most of recharging is done while the vehicle is in stationary mode.

The following steps are taken to design an OLEV route:

1. Collect detailed information on vehicle, route characteristics and operating data such as speed scan, headway time intervals etc.
2. Calculate energy consumption in kWh usage to drive the route.
3. Determine optimal placement locations of stationary charging pads and, if necessary, "in-motion" (dynamic) power tracks to replenish the energy used for the route.

Figure 4: OLEV Route Design and Charging Mode



5.5 Return on Investment (ROI)

The return on investment (ROI) analysis evaluates an OLEV system equipped electric vehicles and charging infrastructure by comparing its capital expenses (CAPEX) and operating expenses (OPEX) against other vehicle and charging infrastructure alternatives.

For capital expenses, the following elements are included:

- Road embedded charging infrastructure cost per vehicle
- Vehicle cost

These initial capital expenses are recovered through operating expense savings from:

- Annual fuel cost savings
- Annual maintenance cost savings

Compared to the fuel consumption costs associated with a traditional ICE (internal combustion engine) vehicle, the estimated cost recovery period for an OLEV road embedded charging infrastructure is dependent on the characteristics of the route pattern. Total cost of an OLEV road embedded charging infrastructure is determined by evaluating the route design for optimal placements of stationary charging pads and "in-motion" power tracks to replenish an equal amount of energy consumption for the duration of the route without having to change the operating service level requirements such as dwell times and headway interval times of the fleet. Hence, the OLEV road infrastructure cost per bus will depend on such factors as length of the route; the speed profile of the vehicle; the number of buses on the route; headway time intervals; and the aggregate dwell time available for recharging while in operation.

For a number of public transit applications for city bus routes and major airport terminals, we found that the road infrastructure requirements can be met with only stationary charging for certain routes while in other situations, the route may need as much as 20 per cent road embedded power tracks for dynamic or "in-motion" charging to avoid either changing the service level or purchasing additional vehicles for out-of-service charging sessions.

For a typical public transit fleet operation, our analysis indicates that the road infrastructure cost recovery can range from less than 2 years, if only stationary charging infrastructure is needed, or may extend to 5 years when extra "in-motion" power tracks are required not to compromise the service level. Considering the overall lifecycle of heavy duty vehicles and energy cost trends for fossil fuels versus electricity, the overall cost recovery and return on investment of the OLEV based transit or commercial fleet deployment offer an attractive choice for today's fleet operators.

Acknowledgments

The On-Line Electric Vehicle technology was originally invented by the researchers from Korea Advanced Institute of Science and Technology (KAIST), South Korea.

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