Application of Shaped Magnetic Field in Resonance (SMFIR) Technology to Future Urban Transportation

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Abstract
Transportation with electrified vehicles can reduce global dependence on fossil fuels and reduce the emission of green house gases. Recent developments have been focused on the development of electric vehicles, hybrid electric vehicles and fuel cell vehicles. However, the commercial deployment of electric vehicles has lagged behind due to technological issues in associated with the battery including: price, weight, volume, driving distance, and limited investment in charging infrastructure. Shaped magnetic field in resonance (SMFIR) technology enables electric vehicles to overcome these limitations by transferring electricity wirelessly from the road surface while vehicle is in motion. This work describes the innovative SMFIR technology used in the KAIST online electric vehicle (OLEV) project as well as its impact on the future of urban transportation. The system integration of the power supply into the OLEV and the vehicle system architecture is also discussed.

Keywords:
Electric Vehicle, Transportation, SMFIR, OLEV, Battery

1 INTRODUCTION

Most electric vehicles (EVs) get the electric energy needed for operation from on-board storage devices (i.e. batteries). However, current battery technology provides a very limited travel range with high costs, long charging times, and lower operating efficiencies due to battery weight. These issues must be addressed in order to increase adoption of EVs in both public and personal transportation.

KAIST has been challenging the technological limitations imposed by electric vehicle batteries by developing wireless power transmission technology that allows electric vehicles to charge during operation. This technology limits the need for remote static charging stations and replaces them with charging infrastructure embedded in the road or highway system. From a technical perspective, this strategy enables the designer to transform design constraints into design variables. This not only allows for the development of EVs with substantially smaller and lighter batteries, but also gives engineers greater freedom in designing the charging infrastructure and the on-board energy storage devices. It also allows the EV power management system to be more closely integrated with the electric power train. From a business perspective, this increases vehicle performance, user satisfaction, and business competitiveness, all while protecting the environment.

In this paper, we introduce an overview of the shaped magnetic field in resonance (SMFIR) technology that was developed as part of the KAIST online electric vehicle (OLEV) project. SMFIR is a technological innovation in wireless power transmission capacity and efficiency under dynamic operation. The design parameters and process of the dynamic charging infrastructure are introduced, starting with the required electric power, required wireless power transmission and the design considerations within the vehicle of the OLEV system.

2 BACKGROUND

2.1 Internal Combustion Engine (ICE) age to green transportation

The world is facing a tough challenge in the perspective of climate change and the global energy supply, mainly caused by a heavy dependence on fossil fuels. In 2007, the United Nations Framework Convention on Climate Change (UNFCCC) took initiatives on providing authoritative, timely information on all aspects of technologies and socio-economic policies, including cost-effective measures to control greenhouse gas (GHG) emissions [1].

While there have been active debates with mixed opinions on the global petroleum production forecast, the U.S. Energy Information Administration (EIA) scenario, published in 2002, shows that peak oil production will be reached within a couple of decades, as depicted in Figure 1. The EIA applied a growth rate of 1-3% in the petroleum production profile with the assumption of R/P=10, which means that the amount of known resources (proven reserves) has 10 years of annual production at the current rate of production to create the three curves in Figure 1. The peak annual global production of petroleum will be at its peak between 2030 and 2050 [2].

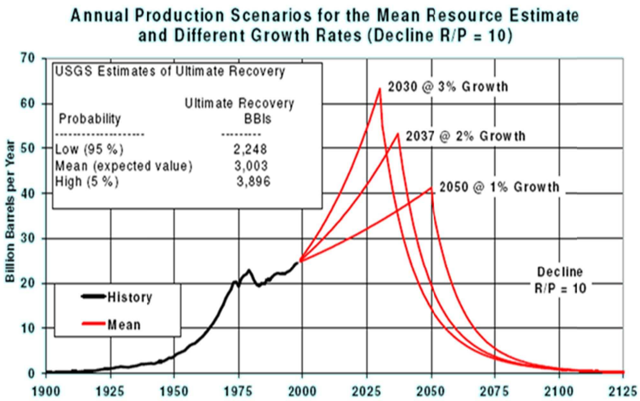


Figure 1: Annual petroleum production scenario by EIA's 2002 international energy outlook [2]

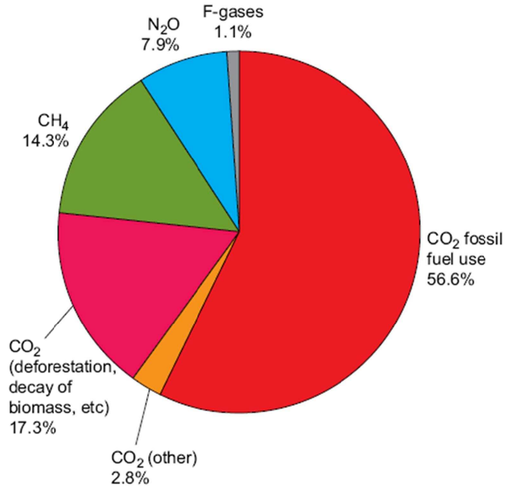


Figure 2: GHG sources distribution [3]

Per the International Panel on Climate Change (IPCC) report published in 2004, the major CO2 sources are from the fossil fuel use, as shown in the Figure 2. According to the EIA, the energy generation and surface transportation sectors showed the biggest growth in CO2 generation during the period from 1970 to 2004, while the industrial, households and the service sectors remained at similar levels [1]. By 2030, the CO2 growth rate on annual basis will be 1.7% per International Energy Agency (IEA), while the EIA's projection is 2.0% without any additional polices on CO2 generation reduction. Moreover the CO2 generation from the fossil fuel will increase by 40-110% by 2030 if there are no additional policies addressing the climate change [1]. Per the IPCC, transportation was responsible for about 19% of the global energy use and 23% of energy-related CO2 emissions in 2004. With the current phase of industrial development, the projected CO2 generation in transportation will increase up to about 50% by 2030 and more than 80% by 2050 [3].

As a global effort, policy makers are developing rules and regulations including public subsidies and awareness to increase fuel economy, and thus reduce their CO2 emissions, on various transportation modes including passenger cars, light-duty vehicles, trucks, aviation and oceanic transportation. The surface transportation industry is putting emphasis on reducing global CO2 generation by improving the vehicle efficiency, developing alternative fuels and introducing new technologies, such as electric vehicles (EVs), plug-in hybrid vehicles (PHEVs) and fuel-cell vehicles (FCVs). Electric vehicles can completely achieve no tail-out emissions and EV stakeholders have put significant efforts into the introduction of electric vehicles to public and private transportation. However, the introduction of those new vehicle technologies are in a limited market penetration phase compared with the growing public's concern on the climate changes, which has been mainly caused by the lack of consumers' acceptance yet.

2.2 Battery technology status

While launching EVs into the market, we believe that the battery is a technological barrier against consumers' desire for a common transportation vehicle. The cost, packaging volume and weight of these batteries in EVs have been major issues, in addition to establishing governmental policies and charging the fuel (power) distribution infrastructure in a local region or nation-wide.

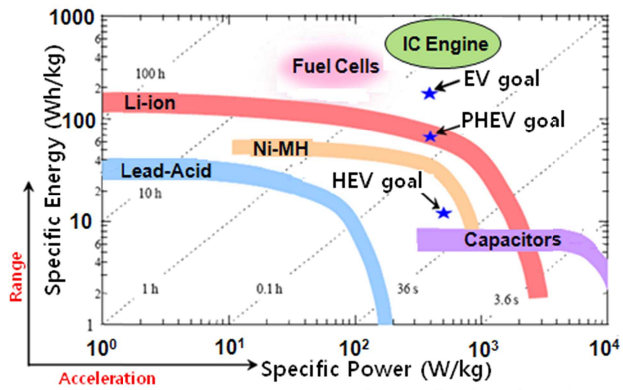


Figure 3: Ragone plot of various electrochemical energy storage and conversion devices [4]

The Ragone plot in Figure 3 shows the positioning of various batteries and energy storage and generation devices in view of specific power density and energy density. For the pure electric vehicle or hybrid electric vehicle application, Li-ion batteries are promising with the current technology level in market. However, the specific power and energy capacity of the batteries are falling short of the IC engines' capacity because of the limited driving range per charging and slow charging time. The United States Advanced Battery Consortium (USABC) set the requirements needed for batteries to be used in EV application in 2003 [5]. These requirements, summarized in Table 1, cover a wide range of issues and include energy and power denoted as HEV, PHEV and EV goal in Figure 3. For example, for the EV application, the required specific power and specific energy are 400W/kg and 200Wh/kg as marked in Figure 3. The current technology status of Li-ion batteries is not enough to meet the required specification.

The projection on the future battery pack price is also an important factor. According to McKinsey & Company's report in 2009, Battery packs now cost about $700 to $1,500 per kWh, but it could drop to as little as $420 per kWh by 2015 under an aggressive cost reduction scenario as shown in Figure 4 [6]. However, the projection is based upon a survey from automotive industries including the assumption of a technological break-through for battery materials and productivity during 2015-2020. The projected cost of the battery packs in the near future will still be a significant portion of electric vehicle cost, which is a barrier to consumers' buying pattern toward eco-friendly transportation.

Parameter(Units) of fully burdened system	Minimum Goals for Long Term Commercialization	Long Term Goal
Power Density(W/L)	460	600
Specific Power - Discharge, 80% DOD/30 sec(W/kg)	300	400
Specific Power - Regen, 20% DOD/10 sec(W/kg)	150	200
Energy Density - C/3 Discharge Rate(Wh/L)	230	300
Specific Energy - C/3 Discharge Rate(Wh/kg)	150	200
Specific Power/Specific Energy Ratio	2:1	2:1
Total Pack Size(kWh)	40	40
Life(Years)	10	10
Cycle Life - 80% DOD(Cycles)	1,000	1,000
Power & Capacity Degradation (% of rated spec)	20	20
Selling Price - 25,000 units @ 40 kWh($/kWh)	<150	100
Operating Environment(℃)	-40 to +50 20% Performance Loss (10% Desired)	-40 to +85
Normal Recharge Time	6 hours (4 hours desired)	3 to 6 hours
High Rate Charge	20-70% SOC in <30 minutes @ 150W/kg (<20min @ 270W/kg Desired)	40-80% SOC in 15 minutes
Continuous discharge in 1 hour - No Failure (% of rated energy capacity)	75	75

Table 1: Requirements on advanced batteries for EV application by USABC [5]

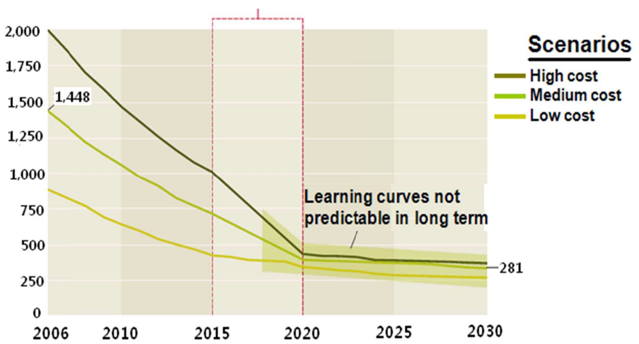


Figure 4: Lithium-ion battery cost projection by McKinsey & Company in 2009 [6]

3 SMFIR TECHNOLOGY AND SYSTEM INETGRATION DESIGN

3.1 Design of OLEV System

The OLEV system includes two major sub-systems: a vehicle and charging infrastructure. The functional requirements (FRs) and design parameters (DPs) of the OLEV system design are covered in Ref. [7] and [8]. Detailed discussion of the design process is beyond the scope of this paper's discussion, but we introduce the outcome of implemented design in the following sections.

3.2 Introduction to SMFIR technology

SMFIR technology (also publically known as an OLEV system) enables the electric vehicle to be charged while the vehicle is in motion. The power cable installed under the road surface can generate a 20 kHz electromagnetic field as depicted in the Figure 5, when the cable gets 20 kHz AC electricity from the power inverter which is controlled under constant current output.

The power converter gets the electricity from the grid with the typical industrial power of 3-phase 380 or 440V. For the bus application, the power capacity of the power inverter has been selected with a 100 – 200 kW range, and can be scaled-up depending on the required electric load of different applications. The pick-up coil sets attached under the vehicle's bottom-floor are tuned to a 20 kHz resonant frequency and are designed to have maximized exposure to the generated magnetic field, which has an optimized field shape for the same purpose. In this way, the transmission efficiency can be maximized while reducing the magnetic field leakage outside of design-intended space.

The design objective is to obtain the maximum power transmission efficiency with the pre-determined level of required power capacity by optimizing the paired power supply and collection system design with the alternate current magnetic field shapes at 20 kHz of resonant magnetic power transmission.

The shaped magnetic field concept and the coverage of the magnetic field by pick-up devices are also shown in a schematic manner in Figure 6. This system is called as a dual type power supply system due to its magnetic shape.

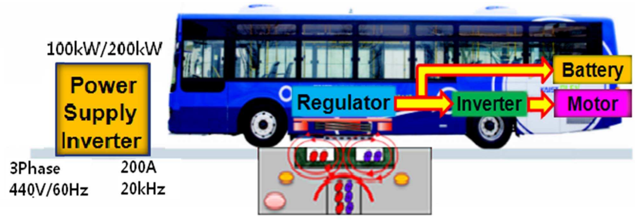


Figure 5: Schematic diagram of SMFIR technology system [9]

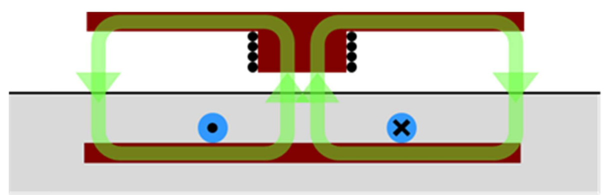


Figure 6: A schematic of shaped magnetic field [9-10]

3.3 Power supply system architecture design

In Figure 7, the shapes of electromagnetic field are shown as the simulation results of the mono and dual types during their numerical iteration process of optimization. The formulation and schemes for numerical simulation are well described in Ref. [9]. With different lay-ups of power cable, combined with different geometries of the ferrite core at the bottom of the cable, the magnetic field shapes, paired with the pick-up devices design, and the resultant performance of wireless power transmission can be different. By placing the ferrite structures in an optimized way, the magnetic field shape can also affect the maximized exposure to the pick-up coils. Numerous design iterations have been performed in order to achieve the maximized power transmission to the vehicle, while reducing the magnetic field intensity to the leakage field.

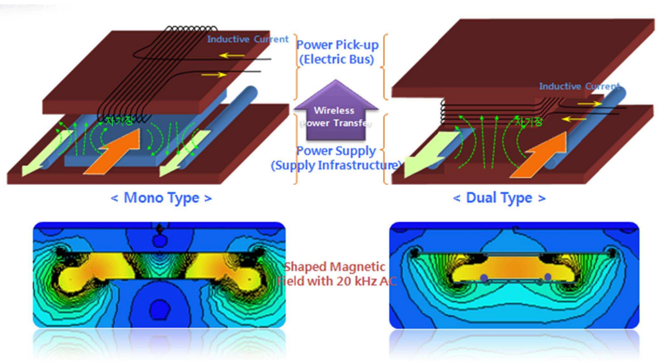


Figure 7: Magnetic field shape from simulations for Mono and Dual Types [9, 11]

As a practical and exemplary application of the SMFIR technology on the road, the powered track is designed as shown in Figure 8. One powered track is composed of a set of segments with different lengths. One segment is a defined length of powered cable loop, operated with single switching mechanism controlled by the power inverter responding to the vehicle identification sensor when the vehicle is approaching to the segmented cable loop. The length of the segment can be a design variable depending on the road conditions, the vehicle speed, the operating condition of acceleration or deceleration, the presence of heavy traffic volume with possible traffic jams or highways, and the presence of BRT (Bus Rapid Transit) lanes. For example, bus stops for public transportation can have a short length of the segment that is approximately the same length of the total pick-up sets installed under the city bus.

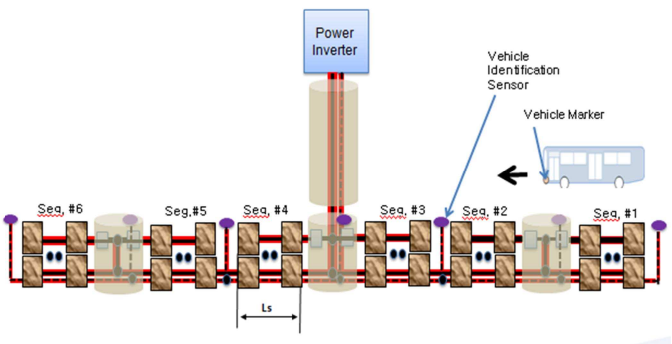


Figure 8: Schematic diagram of single power track architecture with six segments

As an example of a practical design application, KAIST demonstrated the SMFIR technology in Seoul Grand Park with three of six-segmented powered tracks, which are composed of one of 2.5 m and five of 24 m segments as a powered track, respectively, as described in Figure 9. While three powered tracks were composed of six segments, the other had two segments of 2.5 m for the stationary charging while the vehicle was idling and waiting. In the park, the total length of powered tracks is 372.5 m, which is about 17 % of the total travel distance during one-round trip of 2.2 km.

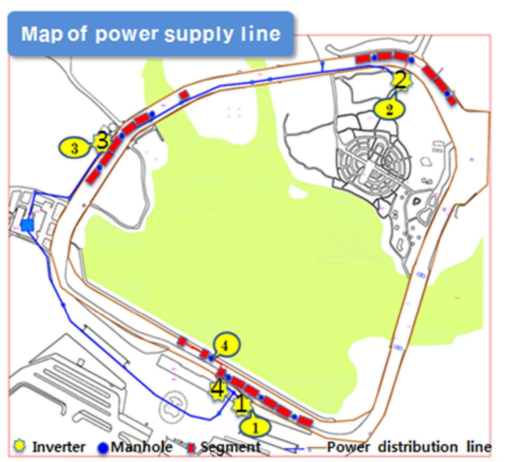


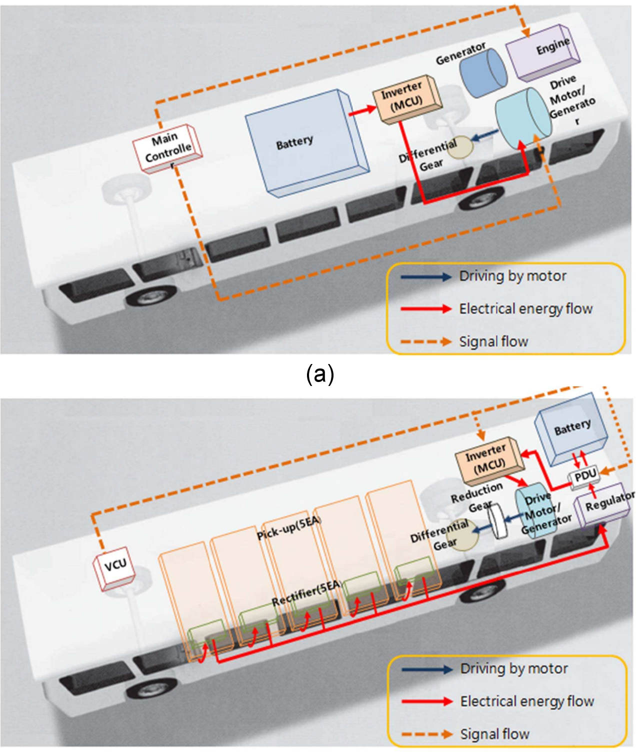
Figure 9: Powered track installation example in the demonstration project in Seoul Grand Park [9, 11-13]

This example design can be applied to other urban transportation applications by modifying design variables such as the lengths of the segments, the combination of different lengths of segments to form a powered track, and the arrangement of the powered track considering the instantaneous required power and averaged electric energy consumption during the vehicle travel. It should be noted that this demonstration project also provides a business case snapshot in applying the SMFIR technology to urban transportation.

3.4 Electric vehicle system architecture

An OLEV can be placed in the category of an electric vehicle because an electric vehicle is defined as a vehicle driven by an electric power train with one or more electric motors and a storage medium for electric energy, usually a battery. The unique difference between an OLEV and a more general electric vehicle is that an OLEV has a set of pick-up devices installed under the vehicle to collect the electromagnetic field energy. A set of electrical devices including rectifiers and regulators, which convert and deliver the electricity in the required form inside the vehicle, must also be installed within the OLEV.

A power control and management system is also necessary within the vehicle such as a Power Distribution Unit (PDU) to control the power flow from the electric source of the battery and the supplied power from the road. The control of the electrical power flow and communication of the necessary signals within a vehicle are also incorporated for the proper operation of the vehicle. In order to show the difference in the system architecture of an OLEV vehicle, a comparison was made between the series hybrid electric vehicle and an OLEV system in Figure 10. Compared with the series hybrid power train, OLEV does not have an IC engine, thus there is no tail-out emission.



(b)

Figure 10: Schematic comparison of power train layout (a) Series hybrid system (b) OLEV system

An example of the physical packaging of the pick-up devices is shown in Figure 11. Depending on the electrical load requirement for a vehicle and the power collecting capacity from one unit of the pick-up device, the proper packaging design can be derived by considering the required vehicle ground height. In the example, four sets of pick-up devices have been installed under the vehicle frame to have the power collecting capacity of 60 kW, while keeping the required ground height of 13 cm.

In buses operating in KAIST campus, the pick-up power capacity is 75 kW with five sets of pick-up devices with the variable ground height of 15-20 cm, providing enough required power to drive full size city buses with 120 kW rated and 240 kW peak power AC induction motor [8, 12].

3.5 Performance parameters and achievements

The critical performance parameters can be defined as follows: power transmission efficiency, vehicle ground height and power capacity. Thanks to the SMFIR technology, we achieved a transmission efficiency of 83% at a ground height of 20 cm and a 75 kW of power capacity. This is a ground-breaking record in the wireless power transfer field, and is a critical performance achievement for the commercial deployment to the future urban transportation.

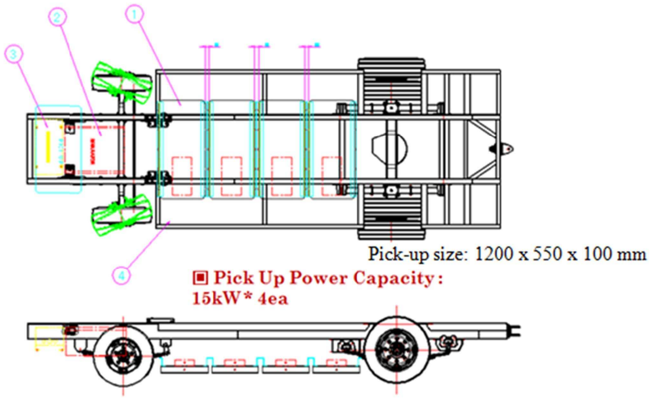


Figure 11: An example of pick-up devices packaging in a vehicle

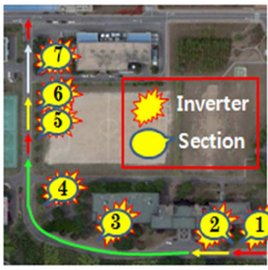
Seoul Grand Park

Section	Length	Inverter Capacity
1, 2, 3	[24m x 5 + 2.5m x 1] each	100kW each
4	2.5m x 2	100kW

Powered track length : 372.5m (16% of entire travel length of 2.1km)

(a)

Mun-ji Campus(KAIST)



Section	Length	Inverter Capacity
1, 5	[5m x 1] each	100kW each
2, 6	[3m x 7] each	100kW each
3, 4	[60m x 2] each	3 : 200kW 4 : 100kW
7	40m x 1	200kW

Powered track length : 390m

(b)

Main Campus(KAIST) (plan in 2011)

Section	Length	Inverter Capacity
1	[10m x 7 + 2.5m x 1]	100kW
2	10m x 7	200kW (common)
3	2.5m x 2	

(c)

Figure 12: Demonstration projects with SMFIR technology

4 APPLICATION OF SMFIR TECHNOLOGY TO URBAN TRANSPORTATION

4.1 Demonstration project as test beds

In addition to the demonstration project described above and summarized in Figure 12 (a), another test bed is under operation at the KAIST Munji campus, located in Daejeon, Korea, as shown in Figure 12 (b). This site has a series of various lengths of segments, 3m, 5m, 40m and 60m, for different application practices. Also it is fully utilized for environmental evaluation and operation monitoring purposes. KAIST is also planning to install another test bed in the KAIST main campus in 2011 as shown in Figure 12 (c).

4.2 Analytic design process for urban transportation application

As part of the engineering design and development process, a new installation has been selected to apply the power supply infra-structure. The subject site will operate a couple of OLEV buses over a 6 km one-way trip, which will take about 20 minutes for each trip. The objective is to design the most efficient and optimized power supply infrastructure. This includes identifying how long the powered track should be, where it should be installed, and what combination of the segments should be laid, in view of the overall energy balance between the energy consumption and charging during operation and the instantaneous power requirement to drive the vehicle.

From the measured (or predicted or required) vehicle velocity profile over time and distance, as shown in Figure 13, it is possible to calculate the required electric power to drive the vehicle of Figure 14, given the vehicle weight, frictional and wind resistance and other vehicle and road information, shown in the equations (1) and (2).

$$F = W\alpha + (R_r + R_a + R_g)W \tag{1}$$

$$P = Fv \tag{2}$$

Here, the variables are defined as follows:

W: vehicle weight [kg]

α: vehicle acceleration [m/sec^2]

R_r: rolling resistance coefficient

R_a: air resistance

R_g: grade resistance ($= \tan\alpha, \alpha$: grade angle)

F: force required to drive the vehicle [N]

v: velocity required for the vehicle [m/sec]

P: power required to drive the vehicle [kW].

From the calculated required power, the energy consumption during one trip can be estimated as shown in Figure 15.

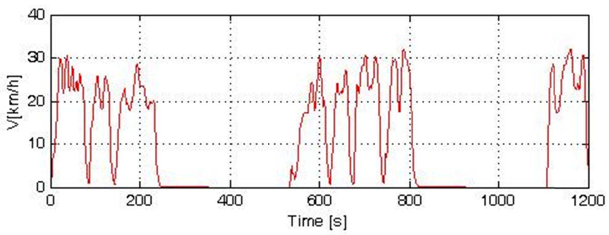


Figure 13: Measured vehicle velocity profile as an initial estimation of operational behavior

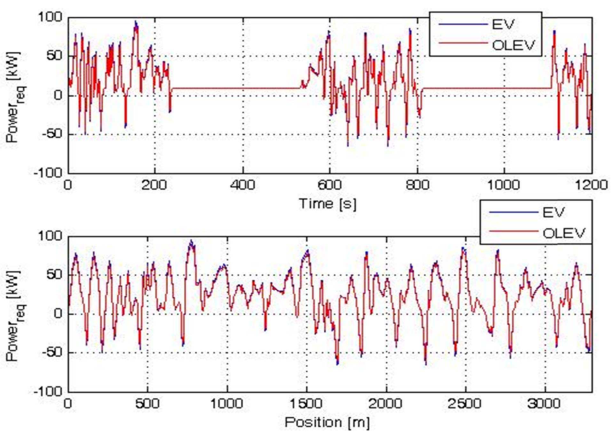


Figure 14: Calculated required electric power to drive EVs and OLEVs over driving time (upper) and over driving distance (lower)

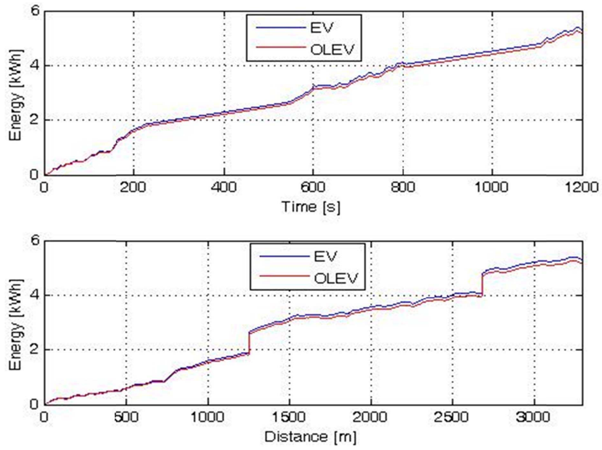


Figure 15: Cumulated energy consumption during one way trip over driving time (upper) and over driving distance (lower)

From the calculated energy consumption per trip and the instantaneous power requirement for the vehicle speed and road conditions, the location and distance of the powered track can be identified with the given battery discharge capacity. In this example, the vehicle is assumed to have a battery with an energy capacity of 25 kWh and the recommended discharge C-rate for the Li-polymer battery is assumed to be C/3, thus the battery in the vehicle can cover up to 75 kW of instantaneous power requirement as shown in Figure 16.

As a rule of thumb, installing the powered track is required where the required driving power exceeds the instantaneous battery discharge power capacity, so that the vehicle can have enough power to be driven. The battery capacity can be an additional design variable as well, but the market status of the battery weight, cost and packaging volume, etc. should be considered at the same time. On the other hand, the power collecting capacity of the pick-up devices is another design variable when determining the battery energy capacity and the power track length design.

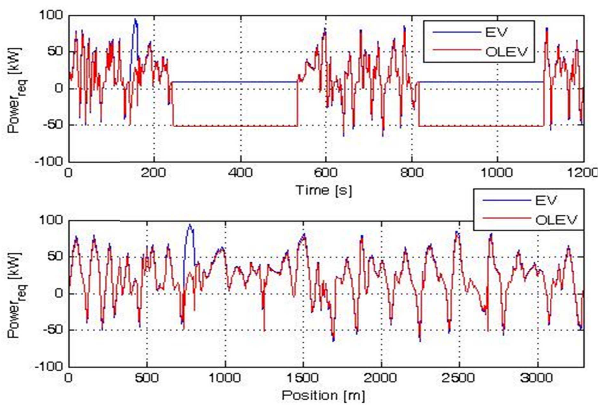


Figure 16: Required electric power by a vehicle with powered track installed over driving time (upper) and over driving distance (lower)

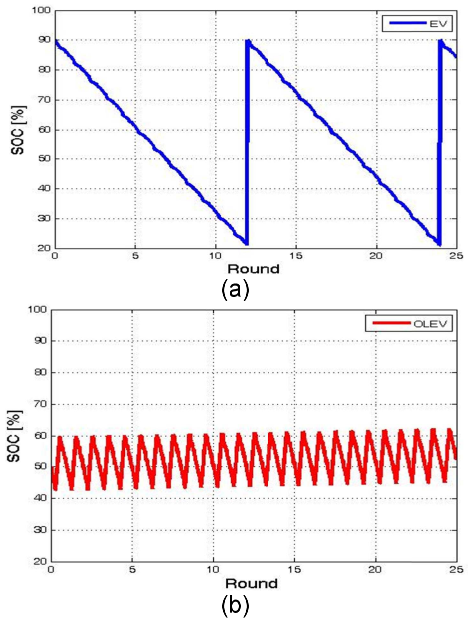


Figure 17: Battery SOC changes during the vehicle operation (a) pure electric vehicle (b) OLEV

By performing the design optimization process considering the prices of the system components, the optimized powered track length combined with the pick-up power capacity and the energy storage capacity of the battery can be determined. While managing the required instantaneous power and the overall energy consumption during the vehicle travel of the closed circuit, the battery status of charge (SOC) should be monitored especially for the Li-ion family battery. One of advantages with the SMFIR technology application in the future urban transportation is being able to manage the battery SOC duty cycle with a lot less bandwidth than the one for the pure electric vehicle, as compared in Figure 17. The pure electric vehicle will have a nearly full duty cycle swinging the SOC from 20 to 90 %, however, OLEV will only swing between 40 to 60 % thanks to its dynamic charging characteristic under operation.

5 SUMMARY

In this paper, the principle of the SMFIR (Shaped Magnetic Field in Resonance) technology has been introduced so that the electric vehicle or OLEV can be dynamically charged from the road surface while the vehicle is in motion. The vehicle system architecture and power supply infra-structure design process and its examples are described and discussed.

For the practical application of SMFIR technology in future urban transportation, the demonstrative test beds are described with the design process while achieving the required performance parameters. With the technology innovation, the fixed design variables, or design constraints, in launching electric vehicles such as the battery energy storage capacity, charging station location, and operating charging distance and time, etc. have been moved to the design variable domain.

Thus, in the view of design strategy for future urban transportation systems, SMFIR technology can provide a greater deal of design flexibility in the charging facility and electric vehicle launch motivated by the CO_2 reduction effort.

6 ACKNOWLEDGEMENTS

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