OPTIMAL DESIGN OF ON-LINE ELECTRIC VEHICLE

Young Dae Ko[1], Young Jae Jang[2]†

[1]*Industrial Engineering & Management Research Institute*
Korea Advanced Institute of Science and Technology, Daejeon, 305-701, KOREA
Phone: +82-42-350-3170, E-mail: ydko@kaist.ac.kr

[2]*Department of Industrial and Systems Engineering*
Korea Advanced Institute of Science and Technology, Daejeon, 305-701, KOREA
Phone: +82-42-350-3130, E-mail: yjang@kaist.ac.kr

Abstract: The On-Line Electric Vehicle (OLEV) is an innovative electricity-powered transportation system which remotely picks up electricity from power transmitters buried underground. Selected as one of "the 50 Best Innovations of 2010" by TIME Magazine, the OLEV is considered as a potential solution for the next generation electric-powered public bus system in Seoul. The prototype of the OLEV based bus has been developed and now a commercialization process is in progress. In this paper, we present a mathematical model and optimization method allocating the power transmitters and determining the capacity of the battery of the OLEV system operating on a fixed route. The Particle Swam Optimization algorithm is used as a solution method.

Keywords: Electronic Vehicle, Green Transportation, Systems Optimization, Transportation System Design

1. INTRODUCTION

1.1 Background

For the last couple of years, numerous ideas for the new electric powered transportation system have been introduced by automakers and researchers to meet the market demand and social and economic requirements. Although some automakers have already introduced concepts and prototypes of electric vehicles – such as "plug-in" electric cars, there are still technical as well as economical limitations in commercializing the products. Most electric vehicles introduced so far use a battery as energy storage, and their energy refilling logistics are similar to those of the IC-engine vehicles – the motor in the vehicle consumes the electric power stored in the battery attached in the car and the battery is charged at a charging station refilling the energy. However, electric cars with this operational concept have a couple of technical problems. First, the per-charge driving distance is short. Compared to the IC engine, the amount of power that could be stored in the battery is limited and therefore, the electric car should be stopped at

†: corresponding author

the charging station to refill the power more often. One way to overcome this problem is to load more batteries in the car. Unfortunately, this solution may not be practical due to the large volume, heavy weight, and expensive price of the battery. Furthermore, a long charging time also limits the commercialization of the current solution. A typical plug-in vehicle requires at least a couple of hour long charging time. This long charging time increases the down-time of the vehicle, and also requires a large area for the charging station to accommodate cars while charged. The On-Line Electric Vehicle (OLEV) is a new concept of the electric transportation system to overcome the limitations of the current existing electric vehicles.

1.2 On-Line Electric Vehicle (OLEV)

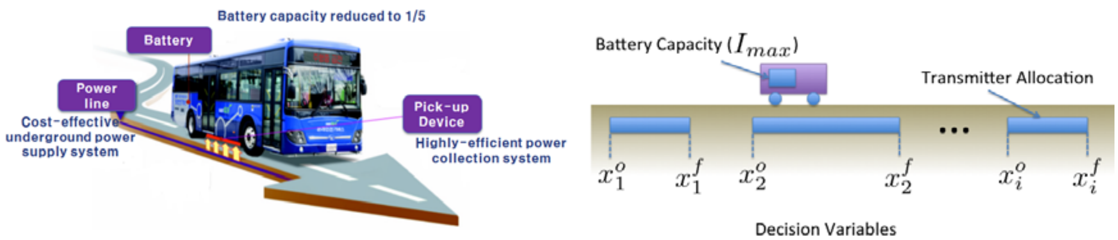

Figure 1 The concept of the On-Line Electric Vehicle

The On-Line Electric Vehicle (OLEV), depicted in Figure 1, is an innovative electricity-powered transportation system which remotely picks up electricity from power transmitters (indicated as "Power Line in the figure) buried underground [1]. The power transmitters – inductive cables buried under the roadway – generate a magnetic field to supply the vehicle with required energy. The power pick-up unit installed underneath the vehicle remotely collects electricity and distributes the power either to operate the motor in the vehicle or to charge the battery. Whether running or being stopped, the OLEV constantly receives electric power through the underground cables. As a result, the OLEV mitigates the burden of equipping electric the vehicle with heavy and bulky batteries. Selected as one of "the 50 Best Innovations of 2010" by *TIME Magazine*, the OLEV is considered as a potential solution for the next generation electric-powered public bus system in Seoul, South Korea [2]. The prototype of the OLEV based bus has been developed and now a commercialization process is in progress. One of the main tasks to achieve successful commercialization of the system is to determine how to economically allocate the power transmitters on the road as indicated in the Figure 1 and how to evaluate the right battery capacity. With given routes and bus operation policies, transmitting enough energy with the power transmitters to the bus is the critical design variable. The allocation of the power transmitters and size of the battery capacity also directly impact the initial infrastructure cost.

Since the OLEV adopts a new concept, not much research has been published yet. Huh *et al*. [3] introduced the state of technology development about the OLEV in terms of the inductive power supply (IPS) system which containing power supply, inverters, power supply rails, pick up modules and a regulator. Suh et al. [1] presented the design concept of the OLEV with Axiomatic Design Theory. They described systems design issues in the OLEV and economic benefit of the system. However, the both papers focus on the hardware of the vehicle and do not rigorously treat the OLEV as a vehicle-transmitters-road integrated system. More detailed previous research related to electric vehicles and wireless electronic power transfer can be found in [4].

1.3 Goal of the paper and problem statement

As a first step in developing the allocation model, we present the OLEV system circulating on a fixed route in this paper. The stations loading/unloading passengers are also pre-defined. Also, we assume that the vehicle operates with a pre-defined velocity profile, and therefore the speed of the vehicle at a specific location on the route is deterministically defined. We assume that the road condition such as up-hill or down-hill angles on the route is also given. With the information, the required energy for the vehicle at a specific point can be evaluated. The installation cost of each power transmitter unit and the power requirement are mathematically analyzed. We propose the particle swarm optimization as a solution methodology. Numerical results are also presented.

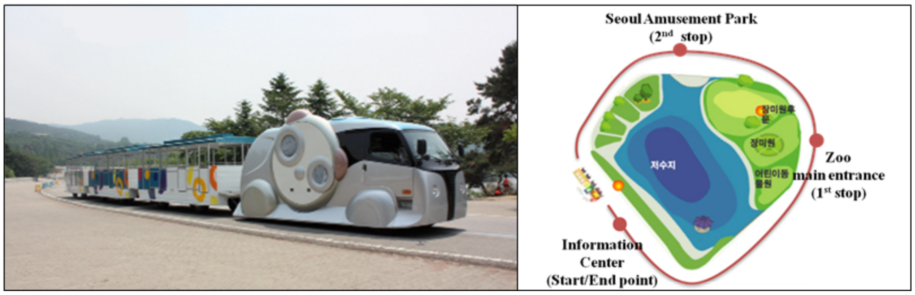

Figure 2 An example of OLEV and its operating route

Although the deterministic assumption and given settings may not perfectly reflect the characteristics of an actual mass transportation system operating in a city, the model could be applied to the OLEV operating in a specialized environment such as the one deployed at the Seoul Amusement Park as shown in Figure 2. The city government of Seoul recently adopted the OLEV technology to the trolley circulating in the amusement park as a test case before applying for an actual mass transportation [5]. The vehicle is running at a speed between 20-40 km/h on the circular route with 2.18km. The main purpose of this deployment was to test the reliability of the new technology, and the cost was not considered as a primary issue. As a result, the transmitter allocation and battery size, which directly impact the total system cost, were not optimized for the system yet. Once the reliability is proven and the system is extended to a longer route, the cost issue is expected to be crucial. Then the optimization method proposed in this paper could be applied. Moreover, the value of the model and optimization method presented in this paper is not limited to the system circulating on a fixed route. This model could be used as a mathematical foundation and it could be extended to more realistic and complex system to be used for a mass transportation.

2. MODEL DEVELOPMENT

For the development of the mathematical models, the following notations and assumptions are adopted.

2.1 Notation

I_{max}	maximum battery capacity of OLEV	$I(t)$	state of charge level of OLEV at time t
k	the number of operating OLEVs	n	the number of power transmitters
x_i^o	starting point of i^{th} power transmitter	x_i^f	ending point of i^{th} power transmitter
t_i^o	arrival time at starting point of i^{th} power transmitter	t_i^f	arrival time at ending point of i^{th} power transmitter
L	length of fixed route	$f(t)$	time-distance relationship of OLEV

I_{high} maximum chargeable battery capacity of OLEV during operation, $I_{high} = \alpha \times I_{max}$ $(0 \leq \alpha \leq 1)$

I_{low} minimum allowed battery capacity of OLEV during operation, $I_{low} = \beta \times I_{max}$ $(0 \leq \beta \leq 1)$

$p(x)$ purchasing cost of unit OLEV which has the x(kWh) as battery capacity

$c(y_i)$ installation cost of power transmitter between x_i^o and x_i^f when $y_i = x_i^f - x_i^o$
I_{CS} charge/supply quantity of electricity for OLEV per unit time
$P_{bat}(t)$ electricity consumption on battery at time t

2.2 Assumptions

1) The k numbers of identical OLEVs are operated separately at fixed route with distance L.
2) Purchasing cost of unit OLEV is represented as a function of maximum battery capacity of OLEV.
3) The n numbers of power transmitters are installed separately, and the installation cost of power transmitter is depended on its installation distance.
4) The charge/supply quantity of electricity for OLEV is proportional to residence time on power transmitter.
5) The state of charge level at initial start point is I_{high} and remaining battery capacity of OLEV during operation should exceed I_{low}.
6) Maximum chargeable battery capacity of OLEV during operation should not exceed I_{high}.
7) Charge/supply quantity of electricity per unit time is always greater than electricity consumption at operating OLEV per unit time.
8) Regenerative braking is assumed to be neglected because the OLEV is operated relatively low speed.

2.3 Mathematical Modeling

Objective Function is the following:

$$\text{Minimize} \quad k \times p(I_{max}) + \sum_{i=1}^{n} c(x_i^f - x_i^o) \tag{1}$$

To optimally allocate the power transmitter for the OLEV operating on fixed routes, we develop the mathematical model with the objective is to minimize the total cost. The objective function (1) is composed of both purchasing cost depending on the maximum battery capacity of k numbers of OLEVs and sum of installation cost of each power transmitter according to its length. Following constraints are considered:

$$I_{high} - \int_0^{t_i^o} P_{bat}(t)dt > I_{low}, \quad \text{where} \quad I_{high} = \alpha I_{max} \tag{2}$$

$$I_{t_i^f} = Min\left\{ I_{high}, I_{high} - \int_0^{t_i^f} P_{bat}(t)dt + I_{CS}(t_i^f - t_i^o) \right\} \tag{3}$$

$$I_{t_i^f} - \int_{t_i^f}^{t_{i+1}^o} P_{bat}(t)dt > I_{low}, \quad i = 1, 2, ..., n-1 \tag{4}$$

$$I_{t_{i+1}^f} = Min\left\{ I_{high}, I_{t_i^f} - \int_{t_i^f}^{t_{i+1}^f} P_{bat}(t)dt + I_{CS}(t_{i+1}^f - t_{i+1}^o) \right\}, \; i = 1, 2, ..., n-1 \tag{5}$$

$$I_{t_n^f} - \int_{t_n^f}^{T} P_{bat}(t)dt > I_{low} \tag{6}$$

$$x_i^o < x_i^f, \quad i = 1, ..., n \tag{7}$$

$$x_i^f < x_{i+1}^o, \quad i = 1, ..., n-1 \tag{8}$$

$$f(t_i^j) = x_i^j, \quad i = 1, ..., n, \quad j = o, f \tag{9}$$

When the OLEV operates at a certain section where no power transmitter is installed, the OLEV does not receive the electricity from the power transmitter and only consumes the electricity stored at its battery. The remaining battery capacity at the end of those sections should always be greater than the minimum allowed battery capacity (=I_{low}). Those requirements are described in Equation (2), (4) and (6). When the OLEV is running where the power transmitter is installed, both electricity consumption and charge/supply are occurring simultaneously. As we mentioned at assumption (7), we assume that OLEV receives the electricity from the power transmitter more than its consumption. Therefore, the state of charge of battery increases when it is operating on the power transmitter as long as the level of charge does not exceed the maximum chargeable battery capacity of OLEV (=I_{high}). Equation (3) and (5) express those characteristics. Equation (7) and (8) describe the physical location order of starting point and ending point for each power transmitter. And equation (9) depicts the time-distance relationship at the both starting point and ending point for each power transmitter.

3. SOLUTION PROCEDURE

The Particle Swarm Optimization (PSO) is a meta-heuristic algorithm introduced by Kennedy and Eberhart [6] in 1995. The PSO was motivated by a social behavior of flocks of bird or schools of fish. Compared to other meta-heuristic optimization methods, the main advantage of the PSO is its simplicity. The PSO requires fewer initial parameters and its searching mechanism is more intuitive. Other applications of the PSO can be found in [7]. In the PSO, the particle means a certain candidate solution. Each particle has its own position (solution), velocity, and best position (solution). To find the best solution of a given problem, each particle moves around in the search space according to the given mathematical formula of their current positions and velocities. Each particle’s velocity is calculated and updated at each step. All particles share their information about their current positions, best positions, velocities, and therefore they can eventually find global best solution. More detailed descriptions about the PSO can be found in [6]. The solution procedures for the optimization problem with the PSO are as follows.

Step 1 Set stopping criterion.
Step 2 Create a population of particles with random positions and velocities.
Step 3 Calculate the fitness value of each particle’s position according to the fitness function.
Step 4 If a particle’s current position is better than its previous best position, update current best position.
Step 5 Find the global best particle.
Step 6 If stopping criteria is satisfied, go to Step 10; else, continue.
Step 7 Update particles’ velocities according to the given formulae of their own best position and global best position.
Step 8 Move particles to their new position according to current position and updated velocity.
Step 9 Go to Step 3.
Step 10 Terminate

4. NUMERICAL RESULTS

The proposed solution procedure is programmed in C++ language and run on a PC with AMD Athlon II X3 450 microprocessor running Windows XP. Since the OLEV system is not in a commercialization stage yet, no exact cost figure is available. For our numerical evaluation, we come up with the following hypothetical cost and price functions with the available information we could collect.

$$\alpha = 0.8,\ \beta = 0.2,\ k = 5,\ p(x) = 400x,\ c(x) = 5000+60y,\ I_{cs} = 800$$

The road condition, battery size, and distance values for the numerical evaluation, we used the information of the existing route in the Seoul Amusement Park shown in Figure 2 – the total distance is 2.18 kilometers and the maximum battery capacity of the OLEV is 20kW. The computation result is summarized in Table 1.

Table 1 The results of numerical example

Total cost	Battery capacity	No. of power transmitter	1st power transmitter	2nd power transmitter	3rd power transmitter	4th power transmitter
64025.4	11kW	4	(425.0, 660.6)	(1140.3, 1194.0)	(1782.8, 1831.0)	(2153.0, 2182.7)

5. CONCLUSION

This study deals with the optimal design of the OLEV system. The OLEV is an innovative electricity-powered transportation system which remotely picks up electricity from power transmitters buried underground. We present the mathematical model of the problem with the objective of minimizing the total cost. The decision variables are maximum battery capacity of OLEVs and number of power transmitters and those allocations. The physical road conditions on the routes are translated into the power requirement at each of unit second. The installation cost of each power transmitter unit and the power requirement are mathematically analyzed. As a solution methodology, we propose the particle swarm optimization. In order to validate the model and solution procedure, we generated and solved an example problem with hypothetical cost values. It was proven that the algorithm generated the solution reliably in a short calculation time.

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