Feasibility Analysis on Ground-level Stations and Wireless Power Transfer Technology Applications for Monorail Systems

Karam Hwang*, Jong-Duk Chung**, Kibeom Lee*, Junyoung Tak* and In-Soo Suh†

Abstract

Subway systems have been a proved method of public transport and are widely used in major cities around the world. However, the time and cost it takes to construct such systems are very high, as it requires underground tunnels. Cities in various countries have implemented monorail systems as public railway transport as it can be more economical and quicker compared to subway systems in terms of construction. In addition, it provides more convenience towards the public as it is not affected to traffic, and also provides an aerial view of the city. However, the overall construction cost for monorail systems is still significantly high, and as a possible solution to further reduce the overall cost, implementation of ground-level stations and wireless power transfer technology has been proposed in this paper. A concept application layout of ground-level stations and wireless power transfer systems has been discussed, using the Daegu monorail Line 3 system as a simulation base. The expected cost for monorail systems implementing ground-level stations and/or wireless power transfer technology has been estimated based on literature survey, and was compared with the current construction cost of Daegu monorail system. Based on comparison, it has shown that implementation of ground-level stations are the most economical, and can be easily implemented for either starting or expanding the monorail line. Implementation of wireless power transfer technology is also economical, but is more feasible when starting a new monorail line as it requires components which will alter the configuration of the train and infrastructure.

Keywords: Monorail, Ground level station, Wireless power transfer

1. Introduction

Major cities around the world are continuously facing challenges with traffic congestion which creates a negative impact to the economy as well as the society [1]. As a method to alleviate these problems, urban railways, especially underground rail transits, have been implemented in major cities [2-4]. However, implementation of such railway systems will become more difficult due to the crowded nature of cities. In case of underground rail transit, construction time and cost are significantly high due to requirement of underground tunnels [5,6]. One possible solution of overcoming these problems is the implementation of monorail systems. Monorail systems were mainly used for short-line systems such as amusement parks or in airport terminals, but are also being used as public transportation systems in various countries [7]. Monorails are known to be a great alternative compared to other urban railway transport, especially underground rail transits, since it requires less time and cost for construction, and having smaller environmental footprint. It also brings a lot of convenience to the passengers since it produces very little noise and vibration compared to other railway transportation systems. In addition, since most tracks are elevated above ground, it provides a comfortable environment for passengers to enjoy the outside view of the city [5,8].

Even though construction of monorail systems may be more economical compared to other urban railway transportation systems, the total cost of construction is still very
high. Since monorail systems have elevated tracks, the stations for passenger waiting areas have to be constructed in elevated platform to match the height level of the tracks. In addition, electrical lines have to be installed throughout the entire track in order to continuously provide power for the train’s propulsion. This inevitably increases the costs in labor and materials for the construction of infrastructure. Therefore, in this paper, ground level station and wireless power transfer (WPT) technology methods are proposed to be implemented into monorail systems in order to minimize the total construction cost. By implementing ground-level stations, the foundation required to match the height level of elevated tracks can be eliminated, thus the overall labor and material costs for construction is expected to be reduced. With the application of WPT technology, it eliminates the need to install electrical lines throughout the entire track. Therefore, this method is also expected to reduce the overall cost in construction. In order to view its application feasibility of the proposed methods, the Daegu monorail line 3 is used as a basis since significant data such as the overall specifications of the railway system, the specification of the monorail train, and cost were readily available. This paper is organized as follows: Section 2 will discuss about the concept of the proposed methods, and also discuss how the proposed methods will be implemented. Section 3 will analyze the expected total cost with the proposed system, and compare with the current conventional monorail system in order to view its application feasibility.

### 2. Proposed Methods

Before discussing the proposed methods, the breakdown cost of the overall construction in monorail systems needs to be analyzed first. Since the Daegu monorail line 3 was used as a basis for the application feasibility of the proposed methods, a cost breakdown estimate of the Daegu monorail line 3 was done as shown in Table 1. The estimates were based on the guidelines given by Urbanaut® Monorail Company were found to analyze the cost breakdown for the Daegu monorail line 3 [9].

Based on the cost breakdown, it can be seen that the major contribution of construction was for the elevated guide way and trains. In addition, the passenger loading/unloading facilities, maintenance and control facility, electrical power, signals, and moving block control, and the fees & contingencies are each responsible for about 10% of the total cost. Here, two methods are proposed that can help reduce the overall construction cost of the system, which are ground level stations, and implementation of wireless power technology for trains.

**Table 1** Cost breakdown of the Daegu monorail line 3 project [9]

<table>
<thead>
<tr>
<th>Item</th>
<th>Portion of total construction cost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevated guide way, including foundations</td>
<td>41.8</td>
</tr>
<tr>
<td>Passenger loading / unloading facilities (2 stations)</td>
<td>8.5</td>
</tr>
<tr>
<td>Maintenance yards &amp; operational control facility</td>
<td>7.2</td>
</tr>
<tr>
<td>Electrical power, signals, and moving block control</td>
<td>7.2</td>
</tr>
<tr>
<td>Rolling stock (28 trains)</td>
<td>26.8</td>
</tr>
<tr>
<td>Fees &amp; contingencies</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Fig. 1. (a) Overall layout of the Daegu monorail track and station (b) proposed ground level station and ramp track

**2.1 Ground Level Stations**

As shown in Table 1, it can be seen that the passenger loading/unloading facilities take a total of 8.5% of the overall construction cost. If monorails are to become ground level, it can reduce the cost of construction significantly, since less materials and labor will be needed compared to when building an elevated station. Fig. 1 (a) shows the current setup of the track and station for the Daegu monorail line 3 and Fig. 1 (b) shows the proposed concept of the track and ground level station.

Fig. 1 (b) shows the measurements of the ground level station. Since the average lengths of tracks between stations are about 800m, the proposed layout has been configured in that length. The average elevation of the track from the ground is around 11.5 m. As shown in the figure, the track starts to go up with a 6% climb, as this is the maximum hill climb that is recommended while maintaining convenience to the passengers by the manufacturer [10]. When the monorail is near its destination, it will go down the ramp at the same grade. There is a 100 m length between the station and the ramp. This is to allow the train to gain some momentum before going up the ramp in
order to reduce energy consumption. It should be noted that this length can be varied depending on the train specification and location.

By implementing ground level stations, the cost of stations can be reduced from 8.5% to 4%, as it will not require as much materials as it did for elevated stations.

### 2.2 Wireless Power Transfer (WPT) Technology

With recent advancements in WPT technology, it is emerging to be used in a wide range of applications. There have already been commercial applications in public transportations, and one example is the bus system in the Korea Advanced Institute of Technology campus [11-13]. When the main power lines are installed inside the road and have the pickup modules installed inside the bus, many issues that currently exist in electric vehicles such as the limited battery capacity size, high cost, long charging time, and the short battery life can be resolved. In [14], a feasibility analysis has been conducted if WPT systems can be applied into rail transportation. Based on the analysis, it has shown that it can meet the performance and safety requirements that are needed for railway systems, and it is well within the needed requirements for monorail systems. A concept layout of wireless power transfer system is shown in Fig. 2.

While there is not a specific method to properly size the power specifications of the WPT for the monorail application, the main goal is to reduce the capacity of the battery. With current WPT technology, the train will not have sufficient power to operate on the WPT system alone, unless WPT power supplies that can deliver peak power of the monorail are installed all along the tracks. This method can become very costly and impractical since there is no difference compared to current monorail power systems.

To determine the minimum size battery capacity, the peak power output of the monorail has to be determined. Even though the peak power output of the monorail has already been determined, the peak power output will be higher, especially when going up on ramps when ground level stations are installed. The peak power output is determined as shown in (1) [15]:

\[ P_{pk} = (ma + c, mg + mg \sin \theta + \frac{1}{2} \rho \_a C_D A V_t^2) V_t \]  

\[ E_b = \frac{(P_{pk} - P_{pu}^*)}{3} \]  

\[ P_{pu}^* \] is the desired power that can be received from the pick-up modules in the monorail. While satisfying the desired power from the pick-up module is important, the sizing of the modules need to be satisfied as well. The equation to determine whether the selected module can satisfy the dimensions of the train is shown in (3):

\[ L_t - \left( L_{pu}^* \left[ \frac{P_{pu}^*}{P_{pu}} \right] \right) \leq L_t \]  

The ideal number of pick-up modules while satisfying the power and dimensions were estimated to be a total of 20 modules, and will give a total power of 2 MW. Based on the calculated needed power for pick-up modules, the required minimum battery capacity in (2) for the monorail system with elevated stations (no slope) and monorail system with ground level stations (with slope) is 397 kWh and 684 kWh, respectively.

### 3. Cost Analysis

#### 3.1 Cost Derivation for WPT technology application in conventional monorail systems and monorail systems with ground-level stations

From section 2.1, it can be seen that ground level stations can reduce the overall construction cost of monorail systems. However, for application of WPT systems, there are more variables involved, so further analysis needs to be conducted. First, the headway time of the Daegu monorail line 3 needs to be determined as shown in (4). This is also the target headway time that must be met when designing the two monorail systems with WPT application (elevated stations and ground level stations). The equation to determine headway time is shown in (5):

\[ T_h = \frac{T_c}{N_t} \]  

\[ T_c = \frac{L_c}{V_t} + \sum_{n=1}^{N_{st}} T_n \]  

Since it is a two-way track, we can assume that the number of trains will be equally distributed to have a balanced
headway time on both ways, which means that 14 trains will be placed on each direction. Based on the estimated average speed of the train and the dwell time at each station, we can determine that the overall headway time is around 187 seconds, or roughly 3 minutes.

From [16], a petri net model was used to derive a methodology to determine the number of buses and inverters that were needed to match the headway time of the original system. With a slight modification to its methodology, the number of monorail trains and the number of inverters were calculated. To determine the required number of trains for the monorail system with elevated stations (no slope) and monorail system with ground level stations (with slope) in order to match the target headway time of the existing system, it can be calculated as shown in (6) to (9):

\[
N_{(elev)} = \left[ \frac{\sum_{n=1}^{N_{stn}} T_n + T_{(elev)}}{T_h} \right]
\]

\[
N_{(gnd)} = \left[ \frac{T_W + \sum_{n=1}^{N_{stn}} T_n + T_{(gnd)}}{T_h} \right]
\]

\[
T_{(elev)} = \frac{L}{V_{t}} + \sum_{n=1}^{N_{stn}} T_n
\]

\[
T_{(gnd)} = \frac{L}{V_{t}} \sum_{n=1}^{N_{stn}} T_n - T_W
\]

As mentioned in section 2.2, the monorail system with ground level station will consume more energy from the train due to the rising ramp, so WPT tracks must be installed along the ramp. Therefore, in (8) and (10), there is an extra variable, \( T_W \), which is the time the monorail takes to go along the WPT ramp track. This is the product of the ratio between the total length of WPT tracks and the total length of the track (both WPT and non-WPT track) and the time it takes for one train to complete one cycle.

From here, the cost of two WPT applied monorail systems can be determined in two factors; train and the infrastructure. In case of the cost for the monorail system with elevated stations, the total cost of the monorail train, \( C_{(elev)} \), and the cost of the infrastructure, \( C_{(elev)} \), can be determined as shown in (10) to (13):

\[
C_{(elev)} = N_{t} C_{t} + N_{p} C_{b} + N_{p} C_{p}
\]

\[
C_{(elev)} = L_{W(\text{elev})} C_{p} + N_{\text{inv,str}} C_{\text{inv}}
\]

\[
N_{\text{inv,str}} = \left[ \frac{\sum_{n=1}^{N_{stn}} T_{(gnd)}}{T_{(gnd)}} \right]
\]

\[
N_{\text{inv}} = \left[ \frac{T_{W}}{T_{(gnd)}} \right]
\]

For \( L_{W(\text{elev})} \), it is assumed that WPT tracks of 100 m length are installed along each station. Based on the number of stations that are available for the Daegu monorail line 3 (total of 30 stations), the total length of WPT tracks are 3 km.

For the monorail system with ground level stations, the cost of train, \( C_{(gnd)} \), and the cost of infrastructure, \( C_{(elev)} \), is shown in (14) and (15):

\[
C_{(gnd)} = N_{t} C_{t} + N_{b(gnd)} C_{b} + N_{p} C_{p}
\]

\[
C_{(gnd)} = (L_{W(\text{gnd})} + L_{W(\text{str})}) C_{p} + (N_{\text{inv,str}} + N_{\text{inv}}) C_{\text{inv}}
\]
additionally install WPT tracks along the climbing ramp. Therefore, the variable $L_W$ shown in (15) is the total length of WPT tracks that are installed on the ramp, which is estimated at 5.778 km based on the diagram shown in Fig. 1(b).

Based on the equations shown from (10) to (15), the estimated cost per headway time for monorails, infrastructure, and total cost for the monorail system with elevated stations (no slope) and monorail system with ground level stations (with slope) are shown in Fig. 3, Fig. 4, and Fig. 5, respectively. It should be noted that the cost was considered for one direction only. Therefore, to determine the cost of two-way direction systems, the determined costs shown in Fig. 3 to 5 needs to be doubled. In Fig. 3, it can be seen that the trend between elevated stations and ground level stations are very similar. The monorail cost for ground-level stations will be slightly higher as it does require a bigger battery capacity. As shown in the figure, the total train cost to match the target headway (marked as a line) of the Daegu monorail system is roughly $100 million and $98 million for the ground-level and elevated station systems, respectively.

In case of Fig. 4, it can be seen that the trend between elevated stations and ground level stations are slightly different, and the gap between the two are significant. This is also expected since it would require more inverters and WPT tracks to be installed along the ramps for the ground-level stations. As shown in the figure, the total cost needed in infrastructure (WPT tracks and inverters) to match the target headway of the Daegu monorail system is roughly $47 million and $19 million for the ground-level and elevated station systems, respectively.

Fig. 5 shows the sum of the train and infrastructure cost for both systems, and it is roughly $147 million and $117 million that is needed to match the target headway of the Daegu monorail system for the ground-level and elevated station systems, respectively.

Using the analyzed data from Fig. 3 to Fig. 5 as a basis, the next section will compare the cost of each system; the conventional system that is being constructed for Daegu monorail line 3, a monorail system with ground-level stations, a monorail system using WPT applications, and a monorail system that applies both ground-level stations and WPT applications. In the next chapter, the four described systems will be expressed as ‘basis’, ‘ground-stn’, ‘WPT’, and ‘WPT ground-stn’, respectively.

3.2 Cost Comparison
In order to establish a fair comparison of the four different systems as mentioned in the last paragraph of the previous section, the cost breakdown shown in Table 1 was used as a foundation. The total cost of ‘basis’ system was distributed to six items listed in Table 1, based on its corre-
sponding percentage and the given specifications of the Daegu monorail station given in the appendix.

From here, the costs of three items in Table 1 (elevated guide ways, maintenance yards & operational control facility, and fees & contingencies) were assumed to be the same for all four systems. It should be noted that the actual cost for implementing for each four systems will vary from the estimates calculated in this paper, depending on the design and location for the construction of each monorail system.

For the ‘ground-stn’ system, the ‘passenger loading / unloading facilities (2 stations)’ cost was the only item that was changed based on the estimates described on Section 2.1. The other five items remained unchanged from the ‘basis’ system.

In case of the ‘WPT’ and ‘WPT ground-stn’ system, the cost of items, ‘electrical power, signals, and moving block control’ and ‘rolling stock’ were changed according to the estimates calculated in Section 3.1. For the ‘WPT ground-stn’ system, the ‘passenger loading / unloading facilities (2 stations)’ were also implemented.

Fig. 6 shows a comparison of the four systems. The costs to implement passenger loading/unloading facilities were $68 million, $32 million, $68 million, and $32 million for the ‘basis, ‘ground-stn’, ‘WPT’ and ‘WPT ground-stn’, respectively. The costs to implement electrical power, signals, and moving block control were $57.6 million, $57.6 million, $29.1 million, and $77.646 million for the ‘basis, ‘ground-stn’, ‘WPT’ and ‘WPT ground-stn’, respectively. The costs to implement the trains were $214.4 million, $214.4 million, $227.8 million, and $233.4 million for the ‘basis, ‘ground-stn’, ‘WPT’ and ‘WPT ground-stn’, respectively.

Fig. 7 shows the total cost of the whole system. The total costs that were estimated were $800 million, $764 million, $785 million, and $803 million for the ‘basis, ‘ground-stn’, ‘WPT’ and ‘WPT ground-stn’, respectively. Based on the comparison, it can be seen that the most economical option is to go with the ‘ground-stn’ system, followed by ‘WPT’. Implementing ‘WPT ground-stn’ will become more expensive than the ‘basis’ system.

4. Conclusion

In this paper, ground-level stations and wireless power transfer (WPT) technology were proposed as methods to reduce the overall construction cost. A concept layout for the ground-level stations was shown, and the cost of implementing these stations was estimated based on literature review. To view its economic feasibility of the two proposed methods, the total construction cost for a monorail system with just ground-level station, a monorail system applied with WPT, and a monorail system with both ground-level station and WPT technology were compared with the current monorail system that is being constructed in Daegu.

Based on analysis, it can be seen that implementing ground level stations can reduce roughly 4% of the total cost of construction for the monorail system in Daegu, which is significant when the total cost of construction is in the range of $800 million. In the case of applying WPT technology, it can reduce roughly 2% of the total cost of construction. The total cost can be further reduced significantly when considering labor costs as well. However, when implementing ground level stations and WPT technology together, the total construction cost will be slightly more expensive. In conclusion, if the city of Daegu plans to expand their line3 in the future, implementation of ground level stations is an option if they expect to reduce the cost of construction while maintaining the current operating system. If Daegu (or any other cities in Korea) expect to start a new monorail line, implementation of WPT technology will also become a more economical option.

## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Acceleration of train (estimated at 1.5 m/s$^2$)</td>
</tr>
<tr>
<td>$A$</td>
<td>Frontal area of train (estimated at 10.5 m$^2$)</td>
</tr>
<tr>
<td>$c_w$</td>
<td>Rolling coefficient of train (estimated at 0.0055)</td>
</tr>
<tr>
<td>$D_p$</td>
<td>Drag coefficient (estimated at 0.26)</td>
</tr>
<tr>
<td>$C_w$</td>
<td>Cost of power lines to allow WPT transmission (estimated at $3500/m$ [16])</td>
</tr>
<tr>
<td>$C_b$</td>
<td>Cost of battery per kWh (estimated at $700/kWh$ [16])</td>
</tr>
<tr>
<td>$C_{d(elev)}$</td>
<td>Total cost of infrastructure required for conventional monorail system (elevated track)</td>
</tr>
<tr>
<td>$C_{d(gnd)}$</td>
<td>Total cost of infrastructure required for monorail system with ground-level stations</td>
</tr>
<tr>
<td>$C_{inv}$</td>
<td>Cost of inverter (estimated at $2.7$ million for a 2MW module [16])</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Cost of pick-up modules (estimated at $10000$ per unit [16])</td>
</tr>
<tr>
<td>$C_{t(elev)}$</td>
<td>Total cost of monorail trains required for conventional monorail system (elevated track)</td>
</tr>
<tr>
<td>$C_{t(gnd)}$</td>
<td>Total cost of monorail trains required for monorail system with ground-level stations</td>
</tr>
<tr>
<td>$C_t$</td>
<td>Cost of each monorail train (estimated at $7.7$ million)</td>
</tr>
<tr>
<td>$E_{min}$</td>
<td>Minimum battery capacity</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration (9.81 m/s$^2$)</td>
</tr>
<tr>
<td>$L$</td>
<td>Overall length of monorail track (23.95 km)</td>
</tr>
<tr>
<td>$L_{pu}$</td>
<td>Length of pick-up module (0.58 m for currently available pick-up module)</td>
</tr>
</tbody>
</table>
$L_{pu}$: Length of each pick-up module (measured at 0.58 m [14])

$L_{t}$: Length of train (46.2 m)

$L_{ran(ev)}$: Length of Wireless Power Transfer (WPT) tracks along the climbing ramps for ground-level station systems (estimated at 5.778 km)

$L_{ran(stn)}$: Length of Wireless Power Transfer (WPT) tracks along the stations (estimated at 3 km)

$m$: Mass of train (estimated at 132 tons at full capacity)

$N_{b(ev)}$: Capacity of battery needed for the elevated station system (estimated at 397 kWh)

$N_{b(gnd)}$: Capacity of battery needed for the monorail system with ground-level stations (estimated at 684 kWh)

$N_{inv}(e_v)$: Number of inverters required to power WPT tracks along the climbing ramp

$N_{inv(stn)}$: Number of inverters required to power WPT tracks in the station

$N_{p}$: Number of pick-up modules (estimated at 20 modules per train)

$N_{stn}$: Number of stations (30 stations)

$N_{tr}$: Required number of trains for a monorail track with ground-level stations (combination of non-elevated and elevated tracks)

$N_{tr(ev)}$: Required number of trains for a conventional monorail track (elevated track)

$N_{t}$: Number of monorail trains (28 trains)

$P_{pk}$: Peak power

$P_{pu}$: Power of each pick-up module (rated at 100 kW [14])

$P_{wu}$: Desired total power of pick-up module in train

$T_{hp}$: Headway time between monorail arrivals

$T_{wh}$: Time it takes for monorail to complete one cycle

$T_{dw}$: Dwell time at each station (estimated at 15 seconds)

$T_{wh}$: Time monorail takes to go along the WPT ramp track

$T_{(elev)}$: Time the monorail travels along a non-WPT track at a conventional system

$T_{(gnd)}$: Time the monorail travels along a non-WPT track at a system with ground-level stations

$\rho$: Air density (1.204 kg/m$^3$)

$V$: Velocity of train (estimated to go up to 40 km/h)

$\theta$: Grade of track (3.43 degrees or 6% for climbing ramp)

References


Appendix. Daegu Monorail Line 3 Specifications

Fig. A.1 illustrates the expected layout of Daegu line 3 monorail system. The total length of the system is 23.95km, with 30 stations. The longest and shortest distance between the two stations is 0.6 and 1.2 km, respectively, and the average length between the stations is 0.8 km. The monorail used for the Daegu line 3 system is provided by Hitachi, and its dimension layout and specifications are shown in Fig. A.2 and Table A.1, respectively. The monorail has 3 cars to form one train and has a total capacity of 265 passengers [8,10,17].

![Fig. A.1. Current subway lines (shown in line 1 and line 2) and the new monorail line (shown in line 3) layout in Daegu](image)

![Fig. A.2. Overall layout of the monorail train for Daegu line 3 system](image)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Hitachi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cars in train</td>
<td>3</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>46.2</td>
</tr>
<tr>
<td>Width (m)</td>
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</tr>
<tr>
<td>Height (m)</td>
<td>5.24</td>
</tr>
<tr>
<td>Top speed (km/h)</td>
<td>80</td>
</tr>
<tr>
<td>Top operational speed (km/h)</td>
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<tr>
<td>Motor rated power (kW)</td>
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<tr>
<td>Number of motors in train</td>
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<tr>
<td>Total rated power (kW)</td>
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