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Development of a statistical analysis model to benchmark the energy use intensity of subway stations

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HIGHLIGHTS

- A multiple regression model for energy benchmarking subway stations is proposed.
- Actual measured and simulation data are utilized to validate the model.
- Weighted values derived from geometry and underground conditions are used.
- Impact factors are compared to define adjusted EUI baseline of subway stations.
- The model evaluates the energy performance of existing subway stations.

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ABSTRACT

This paper presents an Energy Use Intensity (EUI) indicator model for energy benchmarking subway stations.

Among the mass transportation systems, a subway, in terms of its rapidity, punctuality, and efficiency, has been preferred in metropolitan area and recently spotlighted as it mitigates environmental impacts to global warming. Of its several advantages, a subway's carbon footprint is negligible, which directly contributes to energy savings. Therefore, demands of subway systems have increased.

However, subway stations have rarely been included in most energy performance studies and surveys. Due to a lack of information and design complexity, most designers are not able to do optimal design practices.

A statistical model was developed in this study using the benchmark process for 157 actual subway stations in Seoul, South Korea. It includes measured data, utility bills, simulation results, and regression modeling. This adjusted EUI benchmark model was developed using characteristics of subway stations and a statistical validation process. The effectiveness of the model is tested and verified by comparing between measured EUI and adjusted normalized EUI (EUI_{norm}) of actual subway stations. This paper includes the test results of EUI indicator model to benchmark energy performance and assesses existing subway station.

1. Introduction

1.1. Building energy consumption

Buildings in the U.S. accounted for about 41% of total energy consumption in 2010 [1]. Buildings in the U.S. consumed about 74% of total electricity, an increase of 200% since the 1980s [2]. Commercial buildings accounted for about 46% of total buildings (commercial and residential) energy consumption [3].

1.2. CBECS report for building energy benchmarking

The Commercial Building Energy Consumption Survey (CBECS) report provided by US Energy Information Administration (USEIA) and the American Institute of Architects (AIA) guide categorize 14 types of major commercial buildings: Education, Food Sales, Food Service, Health Care, Lodging, Retail, Office, Public Assembly, Public Order and Safety, Religious Worship, Service, Warehouse, Other, and Vacant [4,5]. Also, these reports provide useful information about building geometry and energy consumption. Energy analysts frequently use this information as an energy consumption baseline

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for their energy efficiency projects to reduce buildings' environmental impacts.

1.3. Advantages of subway systems

In general, public transportation systems and buildings are relatively densely constructed in city areas. Among them, the subway is one of the most advanced in terms of reducing direct fossil fuel consumption and traffic loads. Since the first subway transportation system was launched in 1863 in London, it has been rapidly applied to urban areas [6]. Even though initial costs for subway systems are much higher than other ground transportation types, the subway system has been a preferable method that can mitigate the negative environmental impacts and air quality issues. Table 1 compares the fuel efficiency of the four systems. The generic subway system shows about 61.3% and 37.3% more energy efficient than diesel bus system in Vancouver and Santa Barbara, respectively, in 2009 [7].

According to the 2014 Public Transportation Fact Book published by the American Public Transportation Association (APTA), the operating cost per mile of a passenger trip on a subway system (heavy rail) equaled about 44% of the per mile cost of a bus system and 60% of the same on light rail system [8]. Furthermore, most subway stations are constructed underground, requiring only 7% of the maintenance facilities space of bus systems [8].

1.4. Recent studies to improve subway systems

Some studies showed the level of building performance through the analysis of building characteristics such as floor area, number of stories, and occupants characteristics [9,10]. The 2003 CBECS report has been commonly utilized to strengthen the analysis of building performance [11,12].

Many models to predict energy performance has been done for complicated complex buildings. An artificial neural network model, two grey models, polynomial regression models, and geometry based model were used to forecast and compare the future energy demand in the urban buildings [13–15]. Based on Gaussian mixture regression for modeling building energy use with parameterized and locally adaptive uncertainty quantification and real time building simulation method for efficient predictive control of building was made [16,17]. A Gaussian process and 2-stage Data Envelopment Analysis (DEA) model to determine energy savings and uncertainty levels in measurement was studied [18,19]. To determine building energy performance, a mathematical model was proposed, and depending on the building type, saving design method was made [20,21].

Table 1
Energy use of subway and bus system.

Service	All seated passengers	Average energy usage		
		MJ/km	L/km (gasoline equivalent)	mpg (gasoline equivalent)
Generic subway (2.61 kW h/vehicle-km from the environment Canada fact sheet 93-1)	66	9.4	0.29	8.0
London underground	41	10.2	0.32	7.4
Diesel bus in local and express service in Vancouver, BC, Canada	25	24.3	0.76	3.1
Diesel bus in commuter service in Santa Barbara, CA, USA	40	15.0	0.47	5.0

However, some building types and their EUIs have not been defined in the CBECS report, such as airport terminal buildings, hospital, and subway stations. Among those not included in the CBECS report, subway station is one of the complicated building types in which to define energy performance due to the combination of multiple different building types. Leung and Lee developed an interesting approach to predict the energy consumption of railway stations. They adopted the multi-layered perceptron method to mimic the non-linear correlation between energy consumption, the spatial design of the station, and meteorological factors [22]. Thompson assessed the most appropriate methodology for modeling low-energy systems, with reference to their inclusion in the complex environment of an underground railway [23]. Hong and Kim showed the information concerning the trend in subway's energy efficiency and attempted to develop energy conservation measures and analysis [24]. Li et al. used a Computational Fluid Dynamics (CFD) technology to evaluate the indoor thermal conditions of an air-conditioned train station building [25]. Dronkelaar et al. investigated the potential in reducing the heating and cooling energy demand of underground buildings compared to above ground buildings [26]. Ke et al. used subway environmental simulation program with a commercial CFD software program to explore the influence of various operating situations to the subway environment of Rapid Transit System [27]. Casals et al. investigated the electricity consumption of an underground metro station using data from on-site surveys and measurements [28]. Cheng et al. presented solutions for a sustainable urban transportation system by establishing a simplified system dynamics model to simulate the effects of urban transportation management policies [29]. Haghshenas et al. analyzed the impacts of various transportation policies using system dynamics model based on pertinent data of world cities [30].

Several studies focused on gas emission policies and thermal performance of the railway-carriage and tunnels [23,25,29,30]. Subway stations or the impacts of underground conditions were not regarded as major factors [22,23,25,28–30].

1.5. Problem statement

The recent role of subway stations within cities has changed from a simple transportation building to a mixed-use commercial complex including office, retail, and food service building types. Although the number of subway stations has increased rapidly, there is little progress on energy performance studies and surveys. Due to design complexity and lack of information, many designers have not been able to use an optimum-energy model to design energy efficient subway stations.

This paper proposes a statistical model to develop EUI benchmark for subway stations, utilizing survey data and EnergyPlus simulation output data.

2. Methodology

2.1. Overview

In this paper, Eq. (2) is refined through the analysis of weighted values reflecting building composition and underground conditions. All factors and regression coefficients derived from CBECS, SMRT, and simulation results are analyzed to define statistical relations during the process of modifying Eq. (2).

Fig. 1 conceptually describes the methodology phase. In phase I, all building types in the subway station were defined from CBECS and SMRT data. Each squared space represents a specific building type. In phase II, the building types were combined and each impact was modified by weighted value from the analysis of