



Electric train energy consumption modeling



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HIGHLIGHTS

- The study develops an instantaneous energy consumption model for electric trains.
- The model can capture instantaneous braking energy regeneration.
- The model can be used for transportation modeling and system application (e.g. eco-routing, eco-driving).
- The model can be easily calibrated using external data (e.g. speed), without the collection of internal engine data.

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ABSTRACT

The paper develops an electric train energy consumption modeling framework considering instantaneous regenerative braking efficiency in support of a rail simulation system. The model is calibrated with data from Portland, Oregon using an unconstrained non-linear optimization procedure, and validated using data from Chicago, Illinois by comparing model predictions against the National Transit Database (NTD) estimates. The results demonstrate that regenerative braking efficiency varies as an exponential function of the deceleration level, rather than an average constant as assumed in previous studies. The model predictions are demonstrated to be consistent with the NTD estimates, producing a predicted error of 1.87% and –2.31%. The paper demonstrates that energy recovery reduces the overall power consumption by 20% for the tested Chicago route. Furthermore, the paper demonstrates that the proposed modeling approach is able to capture energy consumption differences associated with train, route and operational parameters, and thus is applicable for project-level analysis. The model can be easily implemented in traffic simulation software, used in smartphone applications and eco-transit programs given its fast execution time and easy integration in complex frameworks.

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1. Introduction

The transportation sector has become the major consumer of energy and producer of greenhouse gas (GHG) emissions. Specifically, in 2014, transportation-related energy use accounted for 27% of the total world primary energy consumption and produced 34% of GHG emissions (CO₂) [1]. In the United States, the transportation sector is responsible for 28% of the total U.S. energy use and 34% of CO₂ production [2,3]. The urban transportation system has been deteriorating with regards to the environment given the higher residential density and travel demand, growth in automobile ownership and worsening of traffic conditions. Many cities, especially metropolis areas, are served by a mixture of multiple traffic modes comprised of passenger cars, transit buses, trucks and rail transit. Accordingly, to reduce city-wide energy consumption and GHG emissions, not only are effective strategies required

for each mode, but also integrated strategies considering the interaction of these modes are required. To enable the efficient and cost-effective design and testing of new strategies, a multi-modal simulation system is being developed in order to offer a simulated testbed applicable to multiple traffic modes.

Developing the proposed system requires the design of three modules: passenger car and transit vehicle modeling, subway system modeling, pedestrian and bicycle modeling. This paper focuses on subway system electric rail energy consumption modeling. The developed model will support the overall modeling framework by estimating rail-induced energy consumption and GHG emissions, and designing and testing eco-friendly strategies customized to urban rail transit systems, such as energy-efficient timetables [4,5] and eco-speed control [6,7].

2. Literature review

Energy consumption models can be divided into two categories: forward models and backward models. As demonstrated by [8],

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models that compute the tractive contribution required at the wheels and “work backward” towards the engine are called “backward models”; alternatively, models that start from the engine and work with transmitted and reflected torque are called “forward models”. The use of forward models requires extensive internal engine data. These models are very complex and characterized by slow execution time and high computer memory. Backward models, however, achieve reliable evaluation of vehicle energy consumption based on drive cycle and vehicle characteristic data, without the need to input engine data. In addition, they are characterized by fast computational times and low memory usage, and can be easily implemented in complex frameworks such as simulation and intelligent transportation system (ITS) applications [9]. The backward modeling approach is thus used to develop the proposed modeling framework.

The effort on the review of the literature was made in terms of introducing the details of a subway system along with the system components relative to energy consumption modeling, and the existing backward modeling approaches on rail energy consumption.

2.1. Subway system components for energy modeling

A subway, put simply, is a train and the tunnel through which the train runs. A subway train consists of several connecting cars that contain durable seats as well as poles and straps for people to hold on to when the train is full [10]. The trains, known as rolling stock, are complex given that they include a traction and dynamics system that highly impact energy consumption. For example, the traction system determines how the propulsive force is generated and provided to move a train forward; and the dynamics system determines how a train is accelerated or decelerated thus affecting train transient behavior that highly impacts instantaneous energy consumption. Also, the brake system determines whether the braking power is regenerated to be used or wasted as heat. For regenerative braking, the brake energy can be recovered by converting kinetic energy into a form that can be either immediately used or stored until needed; however, other brake systems, such as dynamic braking, dissipate electric energy as heat rather than using it. Other train characteristics, such as car empty weight, number of axles per rail car and drag coefficient significantly affect the forces acting on a train and thus are also important parameters in energy modeling.

In addition to the train itself, there are several other rail system components, such as track infrastructure and passenger loading, affecting the tractive/braking forces acting on the train. For instance, a good condition track (good rails and cross ties) decreases the starting tractive effort [11]; while a track with steep grades and large curvature results in high resistance forces [11,12]; and passenger loading affects the total railcar weight and thus acting forces. These factors should also be incorporated into the energy modeling framework.

2.2. Existing rail energy modeling approaches

The most widely available measures for rail (either electric or diesel-electric train) energy consumption are those estimated on an annual gross average basis. Specifically, Eqs. (1)–(3) present the modeling approach, where E_p , E_s and E_v are the energy consumed per passenger kilometer (kW h/P·km), per seating kilometer (kW h/S·km) and per vehicle kilometer (kW h/V·km), respectively; E is the annual energy consumption of a rail transit system in kW h; M_p , M_s and M_v are total passenger kilometers, seating kilometers and vehicle kilometers, respectively; C is the train seating capacity and β is the line loss factor associated with the train trans-

mission system. The parameters in the models are readily available from the National Transit Database (NTD) [13–15]. Despite the effortless acquisition of the aggregated measurements, they are not capable of representing the differences in energy consumption associated with route and vehicle characteristics, passenger loading, speed profiles and weather and track conditions, and thereby not suitable for project-level analysis.

$$E_p = \frac{E}{M_p \times \beta} \quad (1)$$

$$E_s = \frac{E}{M_s \times C \times \beta} \quad (2)$$

$$E_v = \frac{E}{M_v \times \beta} \quad (3)$$

Research efforts have thus focused on developing a modeling framework sensitive to the aforementioned system characteristics. An early study conducted by Mittal [16] proposed an analytical method to estimate energy consumption sensitive to speed, train configuration and passenger load. However, the method used average speed for energy prediction without considering speed fluctuation. The model also did not incorporate an energy regeneration module. Some of the state-of-the-art models [17–22] considered an average constant regenerative braking energy efficiently that mainly depended on the train's average speed. The major limitation is that these models cannot capture vehicle transient behavior and model energy regeneration at a microscopic level. Although some of these simplified models have been used to develop energy-optimized strategies [23–28], the validity of the resulting strategies is questionable given the models' inadequacy in instantaneous energy prediction. The National Cooperative Rail Research Program (NCRRP) [29] designed a passenger rail simulation framework which incorporated route and train characteristics, speed, passenger load and regenerative braking into the energy modeling practice. The framework, however, is an excel-based tool and cannot be implemented in more complex frameworks, such as traffic simulation software, smartphone eco-driving and eco-routing systems. Furthermore, the energy prediction within the framework also considers average speed and a constant regenerative efficiency. A recent study [12] initiated a bottom-up modeling framework sensitive to acceleration behavior by incorporating second-by-second speed profiles. Nonetheless, the model cannot generate instantaneous energy regeneration because it assumes a constant regenerative efficiency. The model is also an excel-based tool and thus does not allow for integration in complex frameworks. Other models, such as [30–32], are also not suitable for ITS applications due to their complexity in model specification.

To the authors' best of knowledge, although there have been numerous studies on modeling rail electric consumption, these studies were of limited application especially for road electric vehicles [33–37]. Specifically, they either cannot model train transient behavior or fail to capture energy regeneration at a microscopic level or are not simple enough to be implemented within complex systems (e.g. traffic simulation software and smartphone applications). The paper attempts to fill this void and, for the first time, relates energy regeneration with the instantaneous deceleration level in rail transit energy modeling.

3. Modeling framework

The proposed modeling framework characterizes the energy prediction as two piece-wise functions, as demonstrated in Eq. (4) (energy consumption) and Eq. (5) (energy regeneration). The description of the model parameters is summarized in Table A1

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