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A methodology for determining power demands across urban transport routes

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Abstract: Improving energy efficiency in urban public transport is key for sustainability. Regenerative braking systems help recover energy typically lost during deceleration. However, incorrect system sizing leads to inefficiencies. This study presents a methodology to calculate the instantaneous power demand of a vehicle along urban routes, identifying recoverable power points. The results enable proper system sizing and improved energy use. This approach allows for evaluating the feasibility of regenerative braking, optimizing onboard energy recovery performance, and reducing costs. The method supports decision-making in the design and operation of more efficient, sustainable, and cost-effective urban transport systems.

Keywords: Energy efficiency; Urban; Public transportation; Sustainability; Regenerative braking; Power.

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1. Introduction

Improving energy efficiency is a central objective in the management of urban vehicle fleets, particularly in public transport systems, where cumulative energy consumption is high due to continuous operation across dense, high-demand routes [1]. As cities worldwide aim to reduce emissions, alleviate traffic congestion, and transition toward more sustainable mobility systems, energy optimization becomes a strategic necessity [2]. In this context, regenerative braking systems have emerged as a promising solution. These systems allow for the recovery of kinetic energy during deceleration, which would otherwise be lost as heat, converting it into usable electrical energy that can be stored or fed back into the power system [3].

By reducing net energy consumption, regenerative braking contributes to lowering operational costs and environmental impact. It enhances the overall sustainability of public transportation systems, aligning with several United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [4]. Through technological innovation and smarter energy use, urban transport can significantly reduce its carbon footprint, improve air quality, and enhance the quality of life for city dwellers.

Nevertheless, the performance and cost-effectiveness of regenerative braking systems depend largely on their proper integration with the vehicle's operational context. In many real-world applications, these systems are not optimally sized for the specific characteristics of the routes they service. Undersized systems are unable to capture the full extent of recoverable energy during intense braking, leading to energy losses and missed efficiency gains. Conversely, oversized systems often function below their rated capacity for most of the duty cycle, resulting in unnecessary costs, increased weight, and suboptimal return on investment.

To address this gap, there is a need for data-driven methodologies that allow accurate estimation of power demands and recovery potential along specific urban routes. Understanding the spatial and temporal distribution of power needs—and opportunities for regeneration—is essential for optimizing the design and integration of braking energy recovery systems. This proceeding proposes a systematic methodology for determining the instantaneous power demand of a vehicle along a given route. Using this approach, it is possible to identify braking events with significant energy recovery potential, thereby enabling more efficient, sustainable, and cost-effective implementations of regenerative braking technologies.

2. Methodology

The methodology proposed in this study provides a structured approach to determine the instantaneous power demand of urban transport vehicles and to identify points along the route where kinetic energy can be recovered using regenerative braking systems, as illustrated in Figure 1, which outlines the process in three sequential phases that guide the analysis from data collection to energy estimation

In the first phase, Route Data Collection, operational information is gathered directly from the vehicle's movement along its typical service route, including GPS positions, travel times, and the number of stops, which together define the fundamental inputs needed to reconstruct the route's kinematic behavior under real operating conditions, allowing the subsequent calculations to reflect actual energy requirements and opportunities for recovery

During the second phase, Data Processing, the information obtained is subjected to both kinematic and dynamic calculations that enable a detailed understanding of the forces acting on the vehicle as it traverses different sections of the route, beginning with the kinematic calculation where distance, velocity, and acceleration profiles are derived based on the positional and temporal data captured, these parameters form the basis for estimating the resistive forces encountered during operation, including rolling drag, grading drag due to slopes, and aerodynamic drag caused by air resistance, all of which directly affect the total power demand of the vehicle

Once these resistive forces are quantified, the third phase, Energy Analysis, focuses on calculating the instantaneous power required to overcome these forces and maintain the vehicle's motion, following the principle that power equals force multiplied by velocity, the total power is determined by summing the individual contributions of rolling power, grading power, aerodynamic power, and instantaneous variation of kinetic energy that occurs due to changes in speed along the route, this summation allows the estimation of the net instantaneous power demand, indicating whether energy is being supplied by the propulsion system or if excess kinetic energy is available that could be recovered

When the analysis identifies segments with negative instantaneous power, it reveals opportunities for regenerative braking to capture and store energy that would otherwise be dissipated as heat during deceleration events, these recoverable energy points are crucial for properly sizing the regenerative systems to match the actual recovery potential without oversizing, which can lead to unnecessary costs and inefficiencies, or undersizing, which limits the energy that can be effectively reclaimed

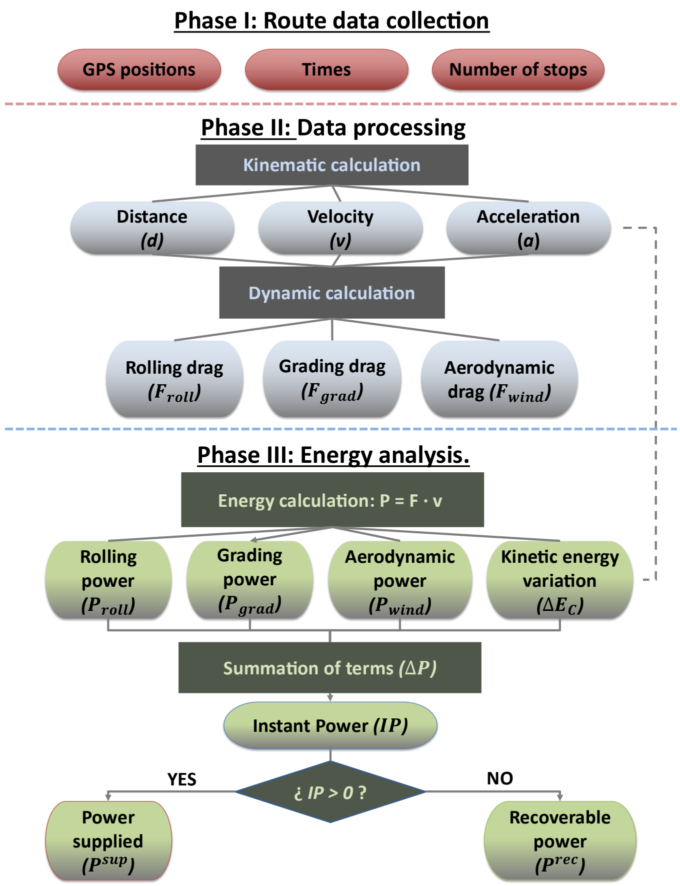

Figure 1: Proposed methodology for calculating instantaneous power demand and identifying recoverable energy points along urban transport routes.

3. Results and Discussion

A detailed simulation was conducted for the six urban bus lines operating in the city of Ávila, generating comprehensive estimates of topographic profiles, instantaneous power demands, and the corresponding recoverable energy available through regenerative braking systems. As an illustrative example, Figure 2 shows the variation of instantaneous power in relation to route altitude and vehicle acceleration over a representative time segment, providing visual evidence of the dynamic energy flows that occur during real urban operation.

The figure highlights how periods of positive instantaneous power, shown in red, correspond to phases where energy must be supplied by the vehicle's propulsion system to overcome resistive forces and maintain motion, whereas negative peaks, shown in green, represent segments where excess kinetic energy is available and could be recovered through regenerative braking. The altitude profile, indicated by the blue line, shows the influence of terrain slope on the vehicle's energy demand, while the acceleration trend line reflects the impact of stop-and-go behavior typical of urban routes.

The results across the six bus lines revealed considerable variability in both peak and average recoverable power values, emphasizing the critical role of route characteristics in determining energy recovery potential. Routes with higher stop density and more pronounced slopes demonstrated more frequent and larger braking events, leading to increased opportunities for energy recovery. Statistical analysis confirmed a strong linear relationship between the amount of recoverable energy per kilometer and two key variables: the number of stops per kilometer and the accumulated slope along the route. This relationship indicates that these two factors are reliable predictors for assessing the feasibility and expected performance of regenerative braking systems.

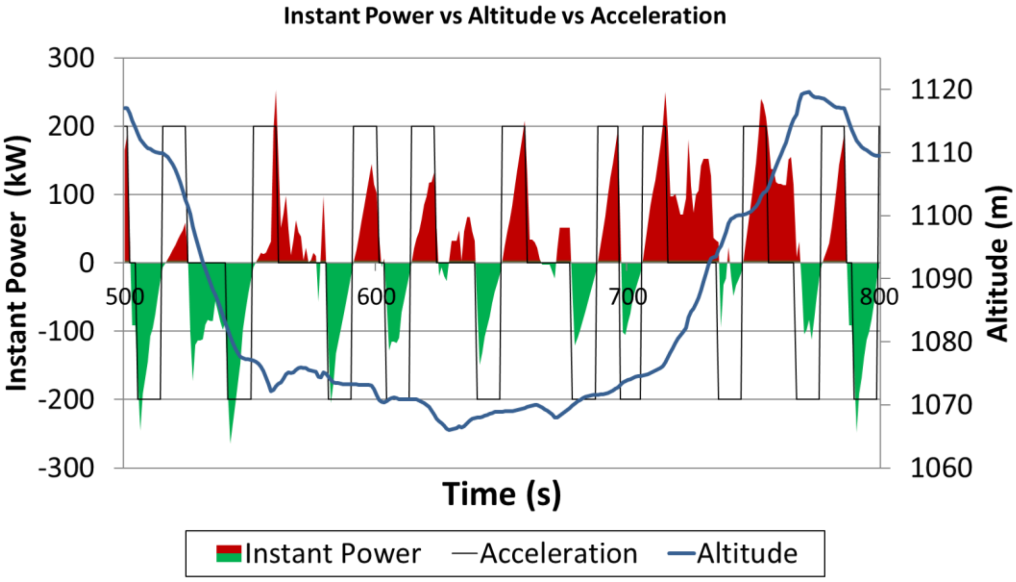

Figure 1: Example of instantaneous power variation along an urban bus route, showing the relationship between instant power, vehicle acceleration, and altitude profile.

Based on these findings, regression models were developed to estimate both the total energy supplied by the propulsion system and the fraction that could be recovered under ideal regenerative conditions. These models enable operators to generate predictive insights into the energy efficiency of different routes, supporting data-driven decisions when prioritizing investments in regenerative technologies or optimizing the operation of existing systems. Notably, routes exhibiting higher stop frequencies and steeper gradients emerge as prime candidates for maximizing the benefits of regenerative braking, as they offer greater potential to capture and reuse kinetic energy that would otherwise be lost as heat.

4. Conclusions

This study demonstrates that a data-driven, route-specific methodology can unlock significant energy savings in urban transport by accurately identifying where and how much power can be recovered through regenerative braking. By revealing the untapped potential hidden in everyday routes, this approach empowers cities to optimize their fleets, cut emissions, and move decisively toward smarter, cleaner, and more sustainable mobility solutions.

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