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Combining Urban Fleet Vehicle Operation with Reducing Energy Wastage in Light Rail Systems

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Abstract

Fleet electric vehicles offer excellent potential for vehicle-to-grid operation, as a result of their predictable use patterns. This paper investigates the potential for linking up urban fleet electric vehicles with wasted energy from urban light rail networks. Vehicle-to-grid charging could be deployed to reduce energy wastage from regenerative braking, while serving as temporary energy storage on the light rail system to reduce energy requirements during acceleration and providing an energy supply for fleets of electric vehicles based in urban areas. This paper uses GPS data from real light rail journeys to estimate regenerative braking energy availability for Edinburgh's light rail network. Findings indicate that electric vehicle charging linked to Edinburgh's light rail network would be beneficial for both parties.

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Peer-review under responsibility of the scientific committee of the 8th International Electric Vehicle Conference

Keywords: Vehicle-to-grid, electric vehicles, fleet vehicles, regenerative braking, light rail

1. Introduction

Urban fleet vehicles such as buses, taxis and delivery vans are increasingly a target for electrification (IEA, 2022). This is in part due to a rise in number and tightening of restrictions for Low Emission Zones (LEZ); thirty-five per cent of light commercial vehicles operating in Edinburgh do not meet the requirements for the LEZ that will come into force in 2024 (City Council of Edinburgh, 2023.). Fleet vehicles tend to follow short, pre-planned routes which can be

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designed to ensure that their range is not exceeded (Tsakalidis et al., 2020). They are also typically stored at depots close to urban areas when not in use. Both route predictability and depot storage make fleet vehicles well-suited to vehicle-to-grid charging. As the estimated time and distance of a vehicle's next journey is known, the required state of charge of each battery is somewhat predictable. Charging can take place at the depot where the vehicles are housed and maintained, or at predetermined points along the route.

Urban light rail transit systems typically have their own power network with dedicated supply substations. When a tram slows down, regenerative braking is employed to convert its kinetic energy into electrical energy, some of which is then reused by the tram to power auxiliary aspects such as heating and lighting. However, much of the energy produced by regenerative braking in light rail vehicles is wasted, as the supply system is not designed to redistribute it effectively. Excess regenerated energy causes the distribution system voltage to rise to Unacceptable and potentially damaging levels, so is disposed of via heat in dump in resistors on the tram roof (Zhang et al., 2020).

Preliminary studies (Zhang et al., 2020) have shown that vehicle-to-grid charging could be employed to reduce wasted regenerative braking energy. Linking urban light rail networks up with bus or delivery depots close to the tracks would allow fleet vehicles to act as temporary energy storage, returning regenerative braking energy to the rail network to reduce the total energy drawn from the substations. Fleet vehicles could also be left in a state of charge appropriate to their next planned use.

While there is strong potential for vehicle-to-grid charging to increase use of fleet electric vehicles in urban areas, the varying nature of light rail geography and use makes it difficult to obtain useful estimates of how much energy is available. Most approaches to modelling energy wastage in light rail systems use simplified network maps and vehicle speed profiles that do not provide a useful representation of overground light rail networks. This paper uses real vehicle motion data collected from journeys on Edinburgh's light rail system, in order to capture the impacts that factors such as track geography have on the potential availability of regenerative braking energy and provide an indicative estimate of how it could be linked with vehicle-to-grid charging for fleet electric vehicles.

Nomenclature	
EV	Electric Vehicle
LEZ	Low Emission Zone
GPS	Global Positioning System
A	Curvature resistance constant
a	Tram acceleration
C	Curvature resistive force experienced by a tram moving around a corner
F_b	Braking force of a tram
G	Gradient resistive force experienced by a tram moving up or down a slope
g	Acceleration due to gravity
h	Track displacement
L_{aux}	Auxiliary load
m	Tram mass
P_a	Regenerative braking power at risk of wastage
P_b	Power produced by regenerative braking
Q	Basic resistive force, experienced by a tram in motion
R	Radius of curvature
s	Track elevation
v	Tram speed
α, β, γ	Davis equation constants for basic resistance
θ	Track slope angle
η_b	Regeneration efficiency of tram motor

2. Methodology

This Section describes the approach taken to determining how much and where regenerative braking energy is wasted along Edinburgh's light rail route, using global positioning system (GPS) data from real journeys. It then explains the methodology used to consider the initial results in the context of fleet electric vehicle (EV) charging.

Edinburgh's light rail network consists of thirteen kilometres of track that serves fifteen passenger stops between Edinburgh Airport at the western end, and St Andrew Square in Edinburgh city centre at the eastern end. Trams always stop at every passenger stop.Electricity is supplied to the network by five dedicated substations. These substations effectively split the network into six distinct energy supply sections, as shown on Figure 1.

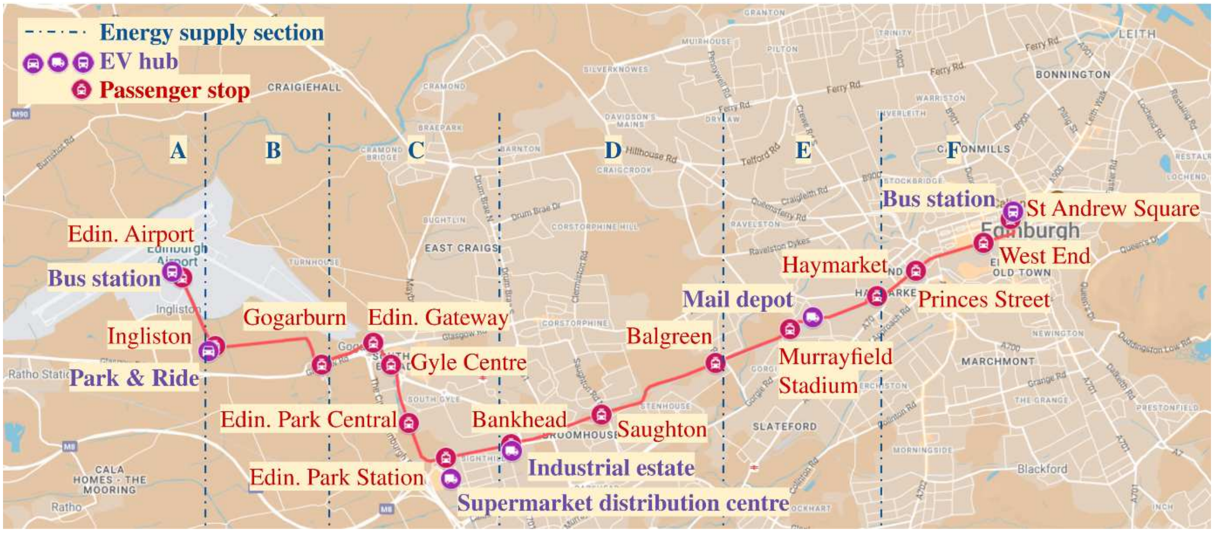

Figure 1. Map showing Edinburgh's light rail network, annotated with passenger stops, energy supply sections, and proposed EV charging hubs.

An extension to Edinburgh's light rail network comprising an additional five kilometres of track, eight more passenger stops and three more electrical substations is due to open for service in summer 2023.

2.1 Modelling energy wastage in Edinburgh's light rail system

The modelling approach adopted in this paper is laid out in Figure 2.

The latitude and longitude of the tram was recorded every second for four journeys (two eastbound and two westbound) along the light rail network between Edinburgh Airport and St Andrews Square.

Information about the tram's position was extracted from the latitude and longitude data and used to determine the total distance travelled so far at each data collection point. This information was then differentiated with respect to time to determine the speed and acceleration of the tram at each point. A Savitsky-Golay filter with a window size of 10 was used to smooth the results.

Basic resistive force, Q, is a function of vehicle speed, v, and key design properties of the tram (Alnuman et al., 2022). These properties are typically quantified by the vehicle manufacturer. It is described by the Davis equation (Chymera et al., 2010):

$$Q = \alpha + \beta v + \gamma v^2 \quad (1)$$

where α represents bearing resistance (N), β represents rolling resistance (Ns/m) and γ represents air resistance (Ns/m^2). The values of these constants could not be confirmed for the exact design of tram used in Edinburgh, so the values for a similar design of tram used in Sheffield, UK were used in this model instead (Balfour Beatty Power Construction Limited, 1991) and are given in Table 1.

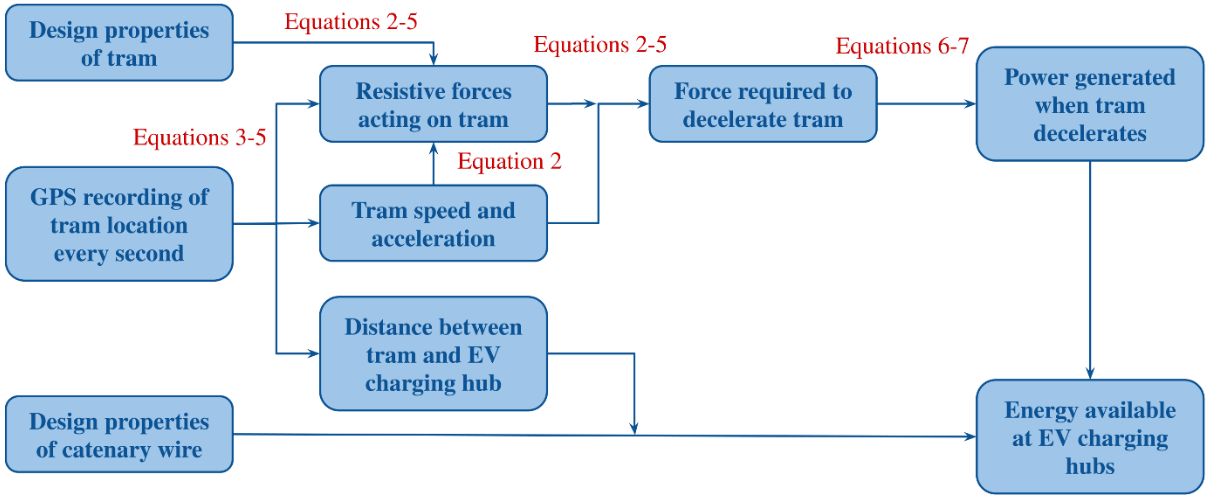

Figure 2. Flow diagram illustrating the approach taken to modelling energy wastage using GPS data.

Table 1. Davis equation constants for Sheffield trams.

Constant	Value
α	1.01
β	0
γ	0.0006

Curvature resistive force, *C*, is the result of the additional friction experienced by a tram's wheels as it rounds a corner. It is given by

$$C = \frac{A}{mgR} \tag{2}$$

where *A* is an experimentally determined constant and *R* is the radius of curvature of the railway track. It is estimated that, for all vehicles travelling below 160 km/h, *A*=600 is a reasonable approximation (Yi, 2017). Since the maximum speed permitted on Edinburgh's light rail network is 70 km/h (Bilfinger Berger – Siemens, 2012), this approximation was used throughout the modelling in this paper. Radius of curvature *R* was measured using Google Earth.

Gradient resistive force, *G*, describes the additional force required for a tram to move up a slope. In order to determine the angle of slope, height difference between data collection points must be known. This information was extracted from the U. S. National Geospatial Intelligence Agency Digital Terrain Elevation Data model via MATLAB (Mathworks Inc., n.d.) for each pair of coordinates. The elevation data was then used to determine the height

$(h_1, h_2 ... h_n)$ of each datapoint. This, in combination with the distance between subsequent datapoints $(s_1, s_2 ... s_n)$, was used to determine slope angle θ,

$$\sin(\theta) = \frac{h_2 - h_1}{s_2 - s_1} \quad (3)$$

which can then be used to determine G at each data collection point:

$$G = mg\sin(\theta) \quad (4)$$

For the purposes of this model, it is assumed that regenerative braking is engaged whenever the tram is experiencing negative acceleration. The power, P_b, generated whenever $a < 0$ is therefore

$$P_b = F_b v \eta_b \quad (5)$$

where η_b is the rated regeneration efficiency as determined by the manufacturer (Bilfinger Berger – Siemens, 2012).

Whenever regenerative braking energy is available, the first priority for its usage is to power the tram's auxiliary functions. These include onboard functions such as lighting, heating and air conditioning. The regenerated braking power at risk of being wasted, P_a, therefore does not include the rated auxiliary load L_{aux} (Bilfinger Berger – Siemens, 2012):

$$P_a = F_b v \eta_b - L_{aux} \quad (6)$$

The energy available at the EV charging hubs shown in Figure 1 and described in Section 2.2 depends on how far the tram is from the hub in the supply section it is currently passing through. This is due to the resistivity of the catenary wire, which is rated at 214 Ω/km (Bilfinger Berger – Siemens, 2012). The energy provided by the tram at each data collection point was calculated based on the power produced at that point, and the distance from the tram to the EV charging hub.

In order to estimate the availability of regenerative braking energy at EV charging hubs for an entire day, average results from the journeys modelled were scaled up according to the total number of light rail services delivered across the network on a typical weekday, as given in Table 2.

Table 2. Total daily journeys on Edinburgh's light rail network.

Direction	Daily journeys
Eastbound	262
Westbound	253

A small number of additional journeys also take place on the network every day to move trams between the depot and start and end points of the network. These journeys have not been factored in because the number is comparatively small, and the trams involved do not stop at stations so engage in significantly less regenerative braking than takes place on a typical journey.

2.2 Investigating means of reducing energy wastage with fleet EV charging

In order to examine how linking up the electrical grid for Edinburgh's light rail system with EV charging could work in practice, an example EV charging hub was selected for each energy supply section. The locations of these hubs can be seen on Figure 1. All EV hubs are based on real businesses or services at the actual locations shown. A range of different businesses and services were selected, in order that a range of different types and capacities of EV be considered. Where possible, some consideration has been given to varying the distance between the EV hub and the substations at either end of the energy supply section. However, a higher concentration of warehouses, park and ride sites and large supermarkets further from Edinburgh's city centre meant that there were fewer options to choose from in the easternmost supply sections; ensuring there was a realistic EV hub option was prioritised over a range of distances from nearby substations.

All but one of the EV hubs selected are linked to businesses or services that would typically use fleets of logistics vehicles. The only exception to this is the EV charging hub for supply section B, which is a Park & Ride site. This is largely due to a lack of other options in the area, however it does also allow for cars to be considered alongside other vehicle types. The vehicle types considered in this study are detailed in Table 3. Information about battery capacities was obtained from vehicle specifications (Renault Trucks SASU, 2022; Waring, 2023.)); where possible, vehicles currently in use in the UK were examined.

Where relevant, multiple vehicle types were considered for a given supply section, in order to investigate a range of different charging situations. As no data has been collected from businesses at this stage, a number of vehicle combinations were proposed for each EV charging hub, with a view towards developing working solutions in future.

Table 3. EV types and battery capacities.

Vehicle type	Battery capacity (kWh)
Cargo bike	0.5
Small car	40
Large car	85
Large delivery van	60
7.5T refrigerated truck	80
18T refrigerated truck	265
Single decker bus	350
Double decker bus	380

3. Results and Discussion

Figure 3 sets out the estimated available energy for each supply section from the four journeys studied. In Figure 4, these results are combined with information from Table 2 to give an indication of the energy available in each supply section on a typical weekday. Finally, Figure 5 contextualises this information in terms of the numbers of different types of EV that could be charged based on the energy available for a typical weekday.

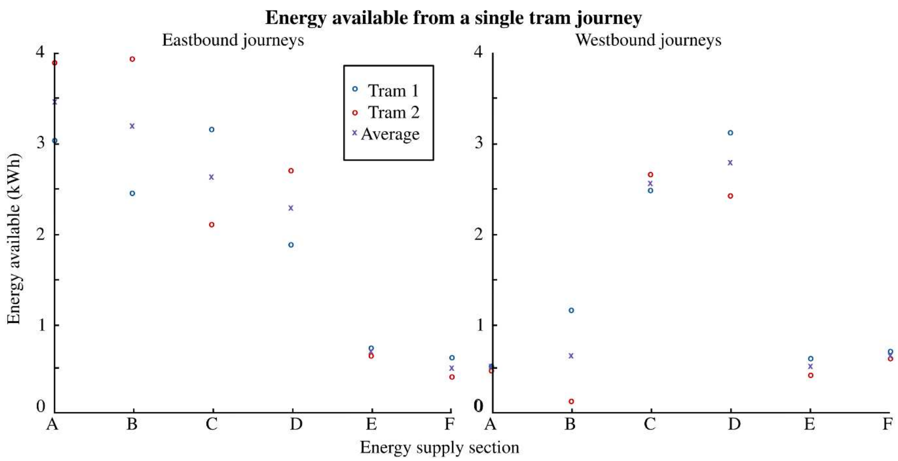

Figure 3. Regenerative braking energy at proposed charging hubs for all (a) eastbound and (b) westbound journeys studied.

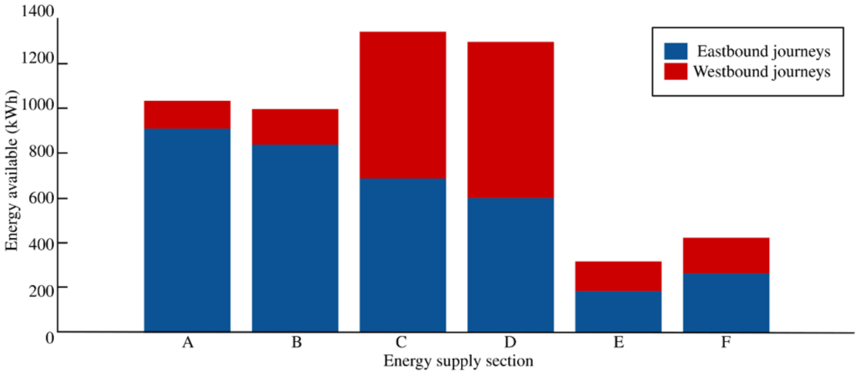

Figure 4. Estimate for the total regenerative braking energy available at proposed charging hubs for a typical weekday.

The results given in Figures 4 and 5 show that there is strong potential to use EVs with vehicle-to-grid charging as temporary energy storage for Edinburgh's light rail system. Figures 3 and 4 give an indication of the extent of the energy saving that may be possible, were such a system implemented. That the majority of the energy available comes from eastbound journeys, as shown most clearly in Figure 4, is to be expected: there are slightly more eastbound journeys per day than westbound journeys, and the asymmetric nature of the light rail system means that there is likely to be more braking in one direction.

As well as highlighting the excellent potential for EV charging linked to Edinburgh's light rail network, Figure 5 shows that a reasonable degree of flexibility is possible in terms of the vehicle types charged. In practice, several of the EV charging hubs selected would use multiple vehicle types. There may also be significant variation in the states of charge required, depending on factors such as vehicle type and time of day. These results therefore provide a starting point from which to develop EV charging strategies with real businesses that increase charging availability and utilise vehicle-to-grid charging to provide energy storage for the light rail system. They also indicate that there is strong potential for such a system to increase EV proliferation and LEZ compliance throughout Edinburgh.

One key limitation of these results is that only four journeys along Edinburgh's light rail system were studied. Such data collection is time-consuming, however further studies should use data from more journeys across multiple times and days, in order to ensure that the samples used for full-day and longer estimates are representative of typical braking behaviour for trams on Edinburgh's light rail network. The data collection methods used did not include any estimation of how the mass of the tram varies along the journey or throughout the day, although this will vary depending how busy a service is. Further studies should consider methods to account for this. However, the most significant limitation of the energy modelling methodology detailed in this paper is that it does not account for energy sharing between trams on the light rail network. All of these limitations impact the actual energy that would be recoverable through EV charging.

4. Conclusions

This paper uses GPS-based modelling to estimate the energy wasted by regenerative braking systems on Edinburgh's light rail network. Options for combining this energy with vehicle-to-grid charging for fleets of various types of EV in order to reduce wastage and increase EV charging accessibility are considered. Results indicate that a range of EV charging combinations could be deployed at EV charging hubs along the light rail network to substantially reduce energy wastage and increase fleet EV use and LEZ compliance in Edinburgh's urban area. Future models should utilise data from more journeys, factor in energy sharing between trams and consider varying vehicle mass to increase the accuracy of energy availability estimates.

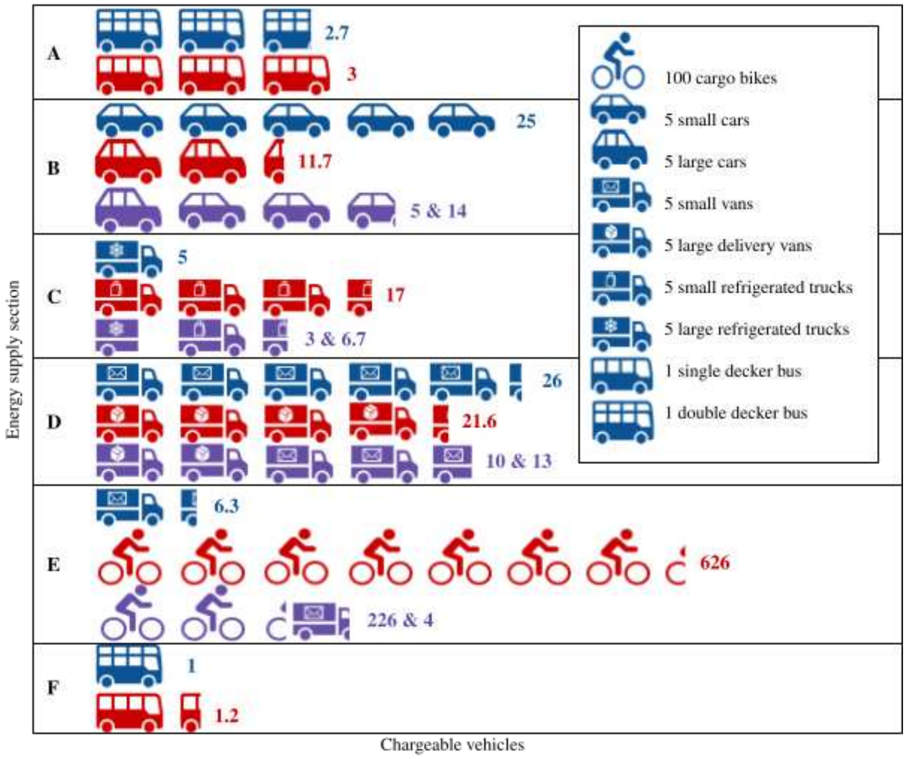

Figure 5. Estimated numbers of different EVs that could be charged by the daily regenerative braking energy at each proposed EV hub.

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