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Energy Harvesting from Road Traffic in the UK – Is It Feasible?

A Master's Dissertation

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A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of Master of Science in the Faculty of Engineering.

Friday 29th August, 2025

Supervisor: Dr. Harry Sansom

Declaration

This dissertation is submitted to the University of Bristol in accordance with the requirements of the degree of MSc in the Faculty of Engineering. It has not been submitted for any other degree or diploma of any examining body. Except where specifically acknowledged, it is all the work of the Author.

V Somesh Kumar Raju, Friday 29$^{\text{th}}$ August, 2025

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Abstract

As global forces are driving the focus on renewable energy, the exploration of omnipresent, yet overlooked, opportunities of ambient energy comes into focus. Vehicles' motion might provide unlimited kinetic energy for electricity generation, but the wide-ranging deployment of such generation systems has been restrained by the incapacity of conventional piezoelectric materials. Being brittle and toxic due to the lead content present in PZT-based materials, conventional piezoelectric materials are grossly expensive for firm infrastructure works; thus, they are almost impractical for a nation-wide implementation on roadways.

The dissertation analyses whether road traffic energy harvesting is possible in the United Kingdom through the exploitation of the novel piezo material, which is 'flexible, environment-friendly, and cheap'-thus addressing the prime drawback of PZT. The study was carried out data-wise, two-stage. **Phase 1** included setting up of a **Road Rating System** applying K-Means on traffic data from the UK Department for Transport so as to identify and rank road segments with the greatest energy-generating potential. **Phase 2** involved the development of the **Future Traffic Prediction Model** for projecting near-future traffic volumes, thereby confirming the sustaining upward trend favoring economic viability.

In conclusion, these studies evidence off this technology's power to cover sovereign local infrastructure needs. The analysis gave a sketch of detail that revealed that considering a high-traffic road section, with a 500-meter stretch of piezoelectric material, more than 2,700 kWh can be generated in just one month. That much energy is enough to keep more than 75 streetlights on continuously. At district-level scaling, in a high-traffic local authority such as Kent, deployment might meet the yearly electric needs of almost 3,000 homes. This research constitutes a powerful quantitative justification to invest in this novel material and a data-supported avenue for the production of sustainable, self-powered road infrastructure in the United Kingdom.

Supporting Technologies

- **Python 3.x:** Primary programming language.
- **Pandas:** Data manipulation and analysis.
- **NumPy:** Numerical operations.
- **Scikit-learn:** K-Means clustering algorithm.
- **PyMC:** Bayesian statistical modeling and probabilistic programming.
- **ArviZ:** Exploratory analysis and visualization of Bayesian models.
- **Statsmodels:** ARIMA and Exponential Smoothing (ETS) time series models.
- **Matplotlib:** Static, interactive, and animated visualizations.
- **Seaborn:** Statistical data visualization.

Acknowledgements

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I also extend my thanks to the University of Bristol for providing the necessary resources and intellectual environment to undertake this study.

Ethics

The focus of this research concerns the examination of publicly available, anonymised road traffic data offered by the UK Department for Transport (DFT), and so no human participants or sensitive personal data were involved. Since this project aims at promoting sustainable energy solutions, one may safely assume it to be a societal and environmental benefit anyway.

All assumptions concerning material properties, and their respective system efficiencies, remain clearly stated to keep the seriousness of the academic discipline intact. **No formal ethical committee approval was sought because this study utilised non-sensitive, aggregated, publicly available data.**

Chapter 1

Introduction

1.1 The requirement for Ubiquitous Energy Harvesting

The global journey towards sustainable development is our shared ability to diversify and augment sources of renewable energy. Whilst solar and photovoltaic, wind, and hydropower have attracted immense investment and focus, there lies unchecked potential for tapping ambient energy modes ubiquitous to our everyday lives. One of such ubiquitous and comparatively unexploited sources lies in vehicular traffic-generated kinetic energy. Every moving vehicle injects vibrations and stresses in pavement and hence constitutes an endless, if diffuse, repository of mechanical energy that if properly converted, stands poised to significantly add to localized power needs or even national ones. Convertibility of mechanical vibrations resulting from these inputs of energy with usable electric current using piezoelectric materials has its basis of principle long established, yet its massive deployment on our energy infrastructure development horizon has remained strangely absent from the energy infrastructure horizon.[14]
The chief obstacle preventing the viable deployment of road traffic energy harvesting is embedded in the intrinsic deficiencies of standard piezoelectric materials. For many decades, the workhorse of piezoelectricity has been lead zirconate titanate (PZT). Whilst providing strong energy conversion performance, PZT poses key problems when viewed for quasi-mass deployment within civil infrastructure. Its hazardous constituents of toxic lead give rise to severe environmental and public health concerns across its lifecycle of manufacture, use, and end-of-life disposal. In addition, PZT as a material is inherently brittle and inflexible, and therefore extremely poorly adapted for enduring the dynamic loading and vibrations, and extreme environments of the road network. Its tendency to crack under stress and its prohibitive manufacture costs have made it economically feasible for only tiny fractions of the immense areas of road infrastructure, thereby establishing and maintaining a technological choke-hold which has trapped road energy harvesting in niche deployment or at best, laboratory demonstration scale.

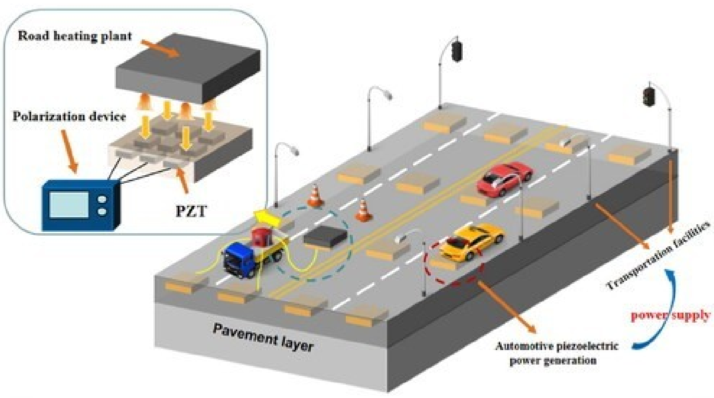

Figure 1.1: A conceptualization of road infrastructure actively generates power from passing vehicles using the piezoelectric materials.[14]

1.2 Motivation for this Research

The author's research group, during the time of this research, was able to invent advanced piezoelectric materials to revolutionize the technology of road traffic energy harvesting. This new piezoelectric material is notably cheaper and universally applicable, unlike commonly used materials such as PZT.
These advances are particularly important because of the significant environmental, mechanical, and financial obstacles that have previously made such systems cumbersome. A turning point in the design of the new collection systems is represented by this material, transitioning from sophisticated mechanical systems that require the use of a thin ceramic to a straightforward, elegant thin film.
The research lies in the domain of materials science and such fundamental renewable energy materials science and offers a strong case for the application of groundbreaking work now poised to entirely disrupt the sector. The primary objective is to provide materials now keen to be developed with the energy infrastructure to tackle the immediate energy sector problem.
The United Kingdom, with its extensive network of roads, presents a real-world potential to apply distributed energy generation. This dissertation fundamentally aims to apply data science to ascertain the feasibility of the new materials, and to provide a rigorous, data-driven analysis that uses these materials in future capital measures. The key goal is to provide, in quantifiable terms, a clear response to the key question of possibilities; is road traffic energy harvesting that would be enabled by this material able to make an impact, and could this be achieved in a sustainable, impactful manner financially?

1.3 Research Aims and Objectives

Research Objectives

The goal of this study is to conduct a comprehensive feasibility study to quantitatively assess the potential of using road-traffic-based energy in the UK using this novel material, by combining two large-scale assessment phases. This project employs a unique structured method of qualitatively summarizing Department for Transport (DFT) public domain data in two steps to provide actionable estimates converted from raw traffic-based data, in turn facilitating the material's strategic use and deployment.

To serve the end goal, the following specific goals are to be worked towards:

- **Road Rating System for Energy Harvesting:** From national DFT as-private-road traffic data, to develop the Road Rating System for quantifying the road characteristics and the energy harvesting potential.
- **Road Rating System & Energy Conversion Model Development (Phase 1):** New road segments will be characterized by the Road Rating System, along with provisions to develop a steady model to convert vehicle kinetic energy for strategic development and deployment of this new piezoelectric material for energy harvesting.
- **Future Traffic Prediction (Phase 2):** Develop multiple near-future Future Traffic Prediction Models for the near-future traffic trends. This analysis will verify the traffic volume projection trend as an extension for the long-term sustainability for renewal of the funding.
- **Feasibility Assessment for Road Illumination & National Grid Contribution:** To determine the feasibility and desire to use the estimated energy to power the standard road lighting system: determination of its desire over the UK, in addition to the contribution to the UK national energy grid.

Chapter 2

Background and Literature Review

2.1 The untapped energy potential of road infrastructure:

It is traditionally thought of that roads are inactive structures that are primarily responsible for the transportation of vehicles. This is not the case; roads could instead offer a boundless energy source. Every day, the vehicles that are driven release a large amount of mechanical energy. This energy gets backed into the road pavements because of the intense vibrations and deformations occurring due to the vehicle's road interaction. This energy goes to waste. The efficiency of the roadways in this scenario is to convert this wasted energy into useable electricity. The research on roadway energy-carrying capacity demonstrates that the road gradient, curvature, as well as the pavement condition and the flowing traffic, directly influence the energy the vehicle consumes[11]. This is fascinating because the deformation occurring in the road because of the vehicles is to some extent quantifiable, which means it can be used by leveraging information technologies in whatever way an adaptive technology deems fit. The energy thus collected could be employed in giving power to the increasing number of low-power street lights and necessary electronic components of intelligent transportation systems in the near future.[14]

2.2 Principles of Piezoelectric Energy Conversion:

Consider the growth of energy from vibrations. One of the most distinguished technologies in the area of generating energy, the piezoelectric technology, is well suited for road application. This is in conjunction with its ability to directly transform energy into solids, and not to mention the enviable energy density. The wellspring of energy, which is why it is known to be the piezoelectric technology, develops when the crystalline lattice of a material is strained due to stress, and a voltage is then generated. This technology also has a couple of governing characters, such as the Piezoelectric theory d_{33} - namely the charge coefficient - and g_{33} - the voltage coefficient - to name a few. The coefficients in question - d_{33} and g_{33} - exhibit great disparities in terms of energy conversion. For example, with common PZT-5A and PZT-4 ceramics lead zirconium titanate, their d_{33} is 390 pC/N and 295 pC/N respectively. On the other hand, with more advanced single crystal ceramics, which also redefines materials with PMN-PT (lead magnesia niobium- lead titanate), their d_{33} is 1285 pC/N, with a g_{33} ratio of 30.6 $\times 10^{-3}$ V/N.[5] With such high coefficients, the PMN-PT materials will be used on the new energy analysis models that are to be developed in this document.

2.3 State-Of-The-Art And Major Challenges:

In the field of road energy harvesting, current studies suggest promising techniques for optimising road performance. The studies also underline the principal aspects obstructing the method's practical implementation. In the research, concrete is usually reduced to a beam on a Winkler foundation, with the assumption that the road is a quarter-car model with the vehicle[13]. The interaction is an indirect one, aimed at forecasting the dynamic strain on the harvester.

In all cases that have been researched, the configuration of the harvesters has a significant role in the amount of power that is produced, as is the case with vehicle weight. Heavy trucks, for example,

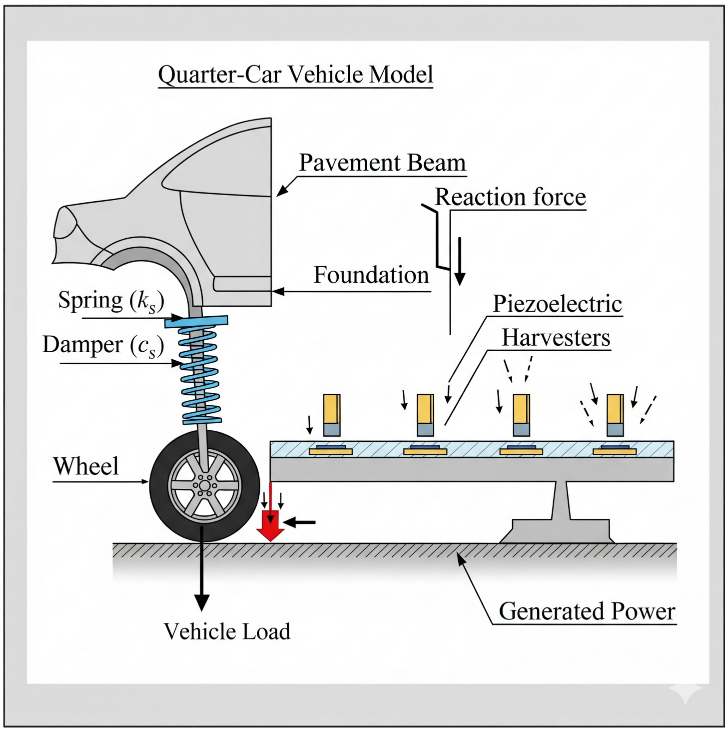

Figure 2.1: The quarter-car model, a common tool in vehicle dynamics for simulating the vertical forces and interactions between a vehicle's wheel and the road surface.[13]

produce far more power compared to sedan vehicles. In the absence of constraints to the configuration of the harvesters, a significantly small distance between the cells is set. The difference is set to ensure the electrical outputs are intelligently accumulated, which is easily achievable as compared to spacing the harvesters at large distances[13]. Improper spacing, especially with the addition of large distances, negatively impacts the harvester and drastically reduces efficiency[13].

More refined modeling of the harvesting has been initiated, however, the technology has been specifically limited to PZT-based ceramic materials. These materials act as the threshold marker for all the high-performing prototypes, starting from the production of milliwatts, and reaching 16 W in the most recent field test in the near future. Despite the progress that has been made in utilizing PZT materials, the challenges of achieving large-scale sustainable road energy harvesting still linger. The primary obstacles towards the aforementioned goals include the brittleness of PZT materials, their nature to tend towards fatigue and fracture under the imposed traffic loads, and the environmental harm as well as public health risks the manufacture of PZT materials imposes.[14] These long-term hitches have meant that until now, road energy harvesting has remained as somewhat of a novelty, used only in limited and strictly controlled situations.

2.4 A Brief History of PZT-Based Road Prototypes:

The style and structure of the energy harvester is of utmost importance. Different types of energy harvesters have been created, including cantilever beam, cymbal, bridge and stacked systems, with each offering their own set of advantages and disadvantages[14].

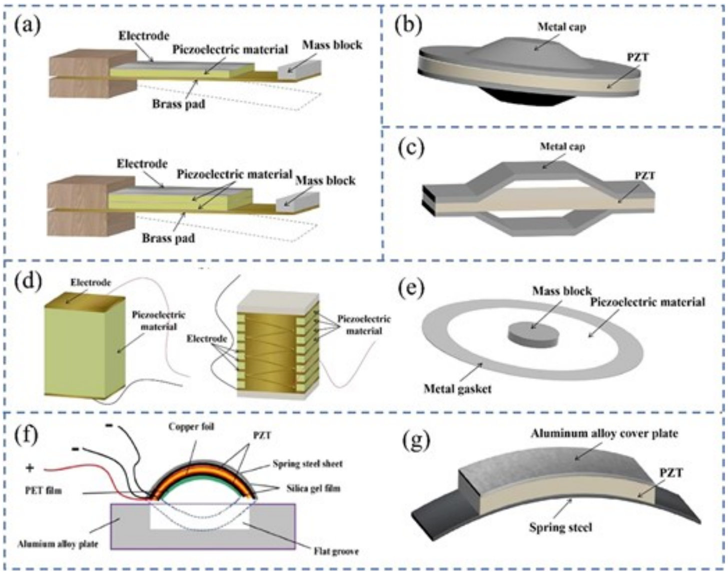

Figure 2.2: Piezoelectric transducer structure; (a) Cantilever structure; (b) Cymbal structure; (c) Bridge structure; (d) Stacked structure; (e) Disc structure; (f) RAINBOW structure; (g) Tile type[14].

In the recent past, wheels have been turning on the subject of road power harvesting. An Israeli company, Innowattech marked this period with an exciting introduction in the year 2008, claiming the innovation of a road power generation system that potentially with a single kilometer of highway, came up to a 250 KW capability. This revelation spurned new interest into experimental studies, such as those that took place in Virginia, in which PZT harvesters were installed and evaluated in the field on a public road by Xiong and Wang.[12]
In the direction of the power level, attainment in terms of watts was made at Hanyang University by a team of researchers, which is a very positive development in light of the raw data regarding the progress. Once achieved, very recent prototype versions have had very promising outcomes. For example, the study made by Wang et al., of the year 2021 had a PEH that demonstrated 16.31 watts which marks the PEH compliance of a road to have a very high level of promise of PZT optimization. These breakthroughs have shown the concept to be quite promising and have also emphasized the need of such breakthroughs to have new materials and PEH to be more durable and environmental friendly in the future.

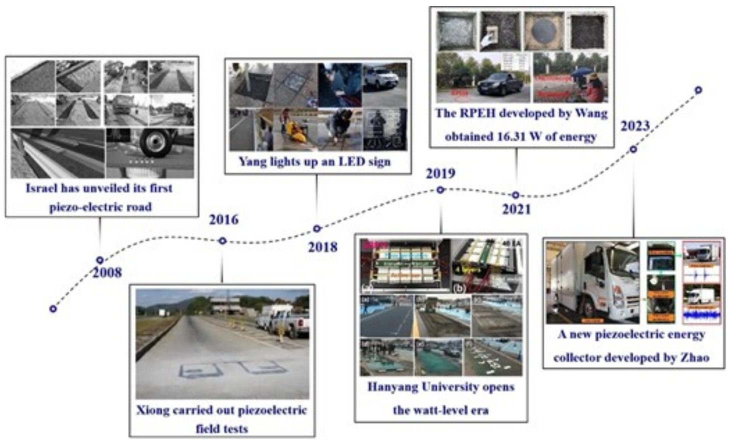

Figure 2.3: Development history of road piezoelectric collection technology.

Chapter 3

Methodology and Execution

In this chapter, the systematic measurements for the study of feasibility of energy harvesting from UK road traffic will be discussed. The methodology is envisaged into two phases: Phase 1 is for the Road Rating System on the basis of current traffic data; Phase 2 is for the Future Traffic Prediction Model for long-term investment analysis. Both feed into the overall energy estimation model.

3.1 Data Acquisition and Pre-processing

The foundation information for this paper is found in the publicly accessible traffic database made available by the UK's Department for Transport (DFT).[1] The Traffic Estimates and TransCore systems, which hold the raw data from the UK's Tame Street Traffic Count data gathering initiative from the previous 25 years from 2021 to 2024 were accessed. These datasets, provided as CSV files, contain crucial information such as Count Point ID, local_authority_name, road_name, link_length_miles, and daily traffic counts for different vehicle categories.
The data acquisition and pre-processing steps involved:

1. **Loading Data:** Each yearly CSV file (Traffic 2021_local_auth.xlsx, Traffic 2022_local_auth.xlsx, Traffic 2023_local_auth.xlsx - Sheet1.csv, Traffic 2024_local_auth.xlsx - Sheet1.csv) was loaded into a pandas DataFrame.

2. **Column Identification:**A new mechanism was developed to identify the proper traffic column (starting with AADF, then all motor vehicles, all HGVs, etc.) and the Count Point ID column, along with the Local Authority and Road Names - this mechanism maintains data uniformity across the various yearly CSV files.

3. **Overview of Road Traffic Data:** The Department for Transport provides an extensive counterpart of public databases, wherein varied traffic statistics concerned with the national road network are recorded. These data typically include:

   - **Count Point ID:** Unique identifiers for specific locations where traffic is counted.
   - **Traffic Volume:** Annual Average Daily Flow (AADF) for various types of vehicles.
   - **Vehicle Classification:** For example, two-wheel motor vehicles, cars and taxis, buses and coaches, LGVs, and different classes of HGV axles (2-rigid, 3-rigid, 4-or-more-rigid, 3-or-4-articulated, 5-articulated, 6-articulated).
   - **Geographical Information:** Location details, including local authority and road names.
   - **Temporal Data:** Annually-downloaded data, providing the ability to analyse trends through time.

4. **Data Cleaning:**

   - Traffic count column values were changed to numerical data type, and non-numeric values were coerced into NaN (Not a Number).
   - Rows with NaN values in the primary traffic column were eliminated.
   - Rows that contained zero or negative counts of traffic were removed because of their irrelevance to the energy harvest calculations.

5. **Merging Datasets:** The yearly DataFrames that were preprocessed were merged into a single comprehensive DataFrame using an 'inner join' on the Count Point ID. Such a step was possibly taken to ensure that only those road segments that measured continuous traffic flow across all the four years (2021-2024) were included for the comprehensive analysis. This newly merged data was then available for the Road Rating System and the Future Traffic Prediction Model.

3.2 Phase 1: Road Rating System Development

The objective of Phase 1 was to develop a system to rate road segments based on their current energy harvesting potential, which is directly proportional to traffic frequency and vehicle composition. This allows for the identification of optimal deployment locations.

3.2.1 K-Means Clustering for Traffic Segmentation

K-Means Clustering has been carried out for the road rating system development. An unsupervised machine learning algorithm is suited for grouping data points into k-set clusters, giving each data point to the cluster whose mean is closest to that data point (centroid)[9].

- **Logic:** Because a more detailed categorization of road segments was sought, five clusters (k=5) were defined in the model. Clustering was carried out with the traffic data of 2024 with two selected variables, `all_HGVs` (total Heavy Goods Vehicles) and `all_motor_vehicles` (total motor vehicles). In rating, considering total traffic volume and proportion of heavy vehicles is two essential points since heavier vehicles directly contribute to the piezoelectric energy generation by virtue of their weights. The algorithm recursively divides road segments into these five clusters to minimize the sum of squared distances between data points and their cluster centroids.

- **Rating Assignment:** After clustering, the mean values for `all_HGVs` and `all_motor_vehicles` were computed for each cluster. The clusters were sorted according to their combined mean traffic volume in ascending order and meaningful labels were assigned to these sorted clusters: 'Very Low Traffic', 'Low Traffic', 'Medium Traffic', 'High Traffic', and 'Very High Traffic'. Directly, it is translated into a rating system such that a higher traffic volume and HGV presence would mean a higher energy harvesting potential.

- **Suitability:** The very simple and efficient K-Means is considered suitable here for large data, for making clear distinctions between different levels of traffic density and composition while classifying the road for energy harvesting potential.

The input to this phase is the addition of a new column, '`Traffic_Rating`' to the DataFrame containing the category for every road segment. Scatter plots and other visualization methods (Figure 3.1) portray the distribution of traffic occurring within these assigned ratings, thereby validating the clustering selection.

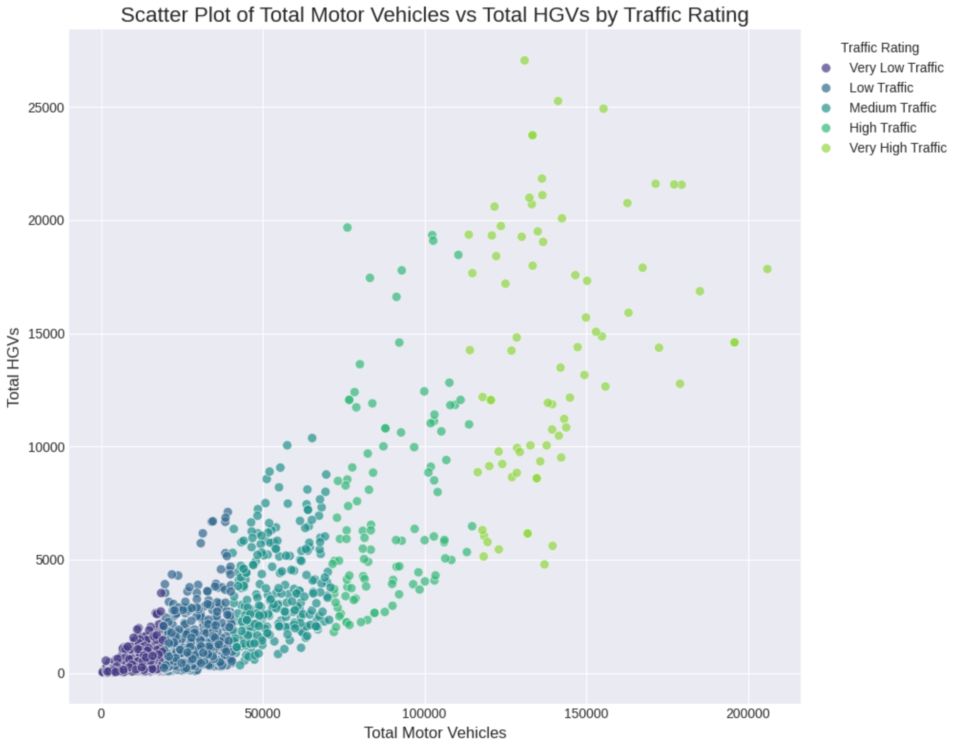

Figure 3.1: Scatter Plot of Total Motor Vehicles vs Total HGVs by Traffic Rating

3.3 Phase 2: Future Traffic Prediction Model

Phase 2 was about the short-term estimating of traffic trends along with long term economic valuation of energy harvesting. This necessitated the implementation and comparison of multiple time series forecasting models.

3.3.1 Model Selection and Implementation

Four types of time series forecasting models were considered for implementation to forecast the 'All Motor Vehicle' traffic for the year 2025 at every Count Point ID.

1. **Simple Growth Model (Geometric Mean):**
   - **Logic:** This model computes the geometric mean of annual growth factors in years 2021-2022, 2022-2023, and 2023-2024, which is applied on 2024 traffic data to estimate traffic in 2025. It is a simple one that considers the average multiplicative trend.
   - **Implementation:** Some custom Python code was written to determine growth factors and use the geometric mean.
2. **Bayesian Linear Regression Model:**
   - **Logic:** In this Bayesian approach, logistic regression fits a linear trend for each "Count Point" ID ($Traffic_{year} = \beta_0 + \beta_1 \times \text{Year} + \epsilon$). Prior probability distributions are set up for β_0 and β_1, which are then adjusted based on historical data from 2021 to 2024 to obtain posterior distributions[2]. Predictions for 2025 are then made by sampling these posterior distributions, so that the mean prediction and the 95 percent Highest Density Interval (HDI) are assigned to calculate respective uncertainty.
   - **Implementation:** The Bayesian modeling and inference were realized with the `pymc` and `arviz` libraries.
3. **ARIMA (AutoRegressive Integrated Moving Average):**

- **Logic:** ARIMA models in their own sense capture the temporal dependencies present in time series data[6]. A simple ARIMA(1,0,0) model (AutoRegressive order 1, Integrated order 0, Moving Average order 0) was applied. Hence, the prediction for the next step is a linear function of the observation at the previous step.
- **Implementation:** Using the `statsmodels.tsa.arima.model.ARIMA` class.

4. **Exponential Smoothing (ETS):**

   - **logic:** Exponential Smoothing models ask for exponentially decreasing weights for more recent observations. In this study, it was Holt's Linear Trend Method (an additive trend without seasonality), which is appropriate whenever the data are exhibiting some kind of trend[6].
   - **Implementation:** According to the documentation, the Exponential Smoothing class can be found under `statsmodels.tsa.holtwinters`.

For each model, historical traffic data for 2021, 2022, 2023, and 2024 represented in a time-series manner (`traffic_ts_pivot`) with years as indices and Count Point IDs as columns was used for individual time-series analysis for each road segment.

3.3.2 Model Comparison and Best Model Selection

After implementing the four series of models, a comparative assessment was then undertaken to select the one best suited for the final traffic forecast for 2025.

Descriptive Statistics and Correlation Analysis: Table 3.1 shows the descriptive statistics of the 2025 forecast from each of the four models.

Table 3.1: Descriptive Statistics for 2025 Traffic Predictions (Multiple Models)

	Traffic_2025_Predicted	Traffic_2025_Predicted_Mean_Bayesian	Traffic_2025_Predicted_ARIMA	Traffic_2025_Predicted_ETS
count	205.00	205.00	205.00	205.00
mean	1,687,914,000	750,740,300	1,583,344,000	1,689,093,000
std	1,889,977,000	499,952,100	1,768,582,000	1,923,002,000
min	1,473,817	0	1,370,391	1,483,087
25%	601,133,700	408,300,800	570,231,100	601,986,300
50%	1,052,539,000	725,420,000	965,733,300	1,023,800,000
75%	1,837,040,000	1,056,631,000	1,701,534,000	1,797,805,000
max	10,142,810,000	2,035,879,000	9,483,859,000	10,410,460,000

The descriptive statistics shows a big difference: the Bayesian model's mean predictions are significantly lower (average 750,740,300) compared to the Simple Growth (1,687,914,000), ARIMA (1,583,344,000), and ETS (1,689,093,000) models.

Table 3.2: Correlation Matrix of 2025 Traffic Predictions

	Traffic 2025 Predicted	**Traffic 2025 Predicted Mean Bayesian**	**Traffic 2025 Predicted ARIMA**	**Traffic 2025 Predicted ETS**
Traffic 2025 Predicted	1.00	0.44	0.99	1.00
Traffic 2025 Predicted Mean Bayesian	0.44	1.00	0.45	0.45
Traffic 2025 Predicted ARIMA	0.99	0.45	1.00	0.99
Traffic 2025 Predicted ETS	1.00	0.45	0.99	1.00

The heatmap clearly shows:

- Correlations nearing 1.0 suggest a strong positive relation between Simple Growth, ARIMA, and ETS Predictions. Somewhat expectedly, these three models would mostly predict similar trends and magnitudes.

- Around the 0.4 to 0.5 mark lies much lower correlation between the Bayesian mean predictions and the other three methods, thus reflecting the very different forecasts produced by the Bayesian model.

Table 3.3: Top 10 Local Authority wise Traffic Predictions (Multiple Models)

Count Point ID	**Local Authority**	**Traffic 2025 Predicted**	**Traffic 2025 Predicted Mean Bayesian**	**Traffic 2025 Predicted ARIMA**	**Traffic 2025 Predicted ETS**
123	Essex	10142810000	738880800	9483859000	10410460000
65	Hampshire	10013790000	613096700	9424325000	10168300000
80	Kent	9954877000	527670100	9327866000	9976520000
135	Surrey	8865761000	0	8213076000	9018953000
78	Hertfordshire	7627514000	0	7183737000	7880271000
76	Lancashire	7602059000	0	7184383000	7659939000
72	Warwickshire	6675116000	1552738000	6097960000	6699120000
114	Staffordshire	6439515000	1529453000	5950541000	6491203000
97	Cambridgeshire	5542039000	661599300	5062458000	5599886000
60	Leicestershire	5475095000	733892700	5137764000	5627551000

Best Model Selection: After the tests of comparing and contrasting, the Simple Growth model was selected for the final forecast of 2025.

- **Reasoning:**
  - **Simplicity and Interpretability:** The Simple Growth model is simple, easy to understand, and represents the historical average growth rate directly measured with data.
  - **Correlation with Other Standard Models:** There is a very high positive correlation between the predictions of the Simple Growth model and those of the models ARIMA and ETS. Because of this strong agreement among multiple standard time series methods, it may be concluded that given this dataset, a simple growth rate captures well the dominant underlying trend. Complex models like ARIMA and ETS would make a poor choice here due to such a limited historical data set of only 4 years because they would probably be fitting noise or might even produce less reliable results since parameter estimation would be less robust.
  - **Bayesian Model Divergence:** The Bayesian model's mean predictions were lower and poorly correlated with the other models. This could be explained either by Bayesian models being notoriously sensitive to prior specifications when data are scanty or problems with the Markov Chain Monte Carlo (MCMC) sampling during its execution (warning about "divergences" and "max tree depth"). Without further domain expertise or ample historical data to validate these lower estimates, relying on them as the main point forecast for breakeven analysis is rather conservative or even erroneous. The frequent forecast of zero traffic for segments with a historical trend of increasing traffic is another worrying factor.

Hence, the Simple Growth model gives a sensible, sturdy, and interpretable forecast for the limited data available, whereas the other standard time series models also happen to support it as a general consensus. It was precisely on this model that some final 2025 predictions were made.

3.4 Energy Estimation Model

The core of the feasibility evaluation rests an accurate estimate of the energy generated by the piezoelectric strips. Herein, traffic data, characteristics of the materials, and vehicle parameters are considered.

3.4.1 Material and Vehicle Parameters

The parameters used for the energy calculations are: representing the properties of the novel piezoelectric materials and the average characteristics of vehicles.

- **Material Parameters:**
  - Piezoelectric charge constant (d_{33}): 1.285×10^{-9} C/N
  - Piezoelectric voltage constant (g_{33}): 30.6×10^{-3} Vm/N
  - Thickness of one piezoelectric strip: 0.005 m
  - Area of one piezoelectric strip: 0.02 m^2
    This is the contact area between tire and piezoelectric element.
- **Vehicle Parameters (Mass and Wheels):** Based on a review of UK government and industry sources, the following average mass estimates were used for each vehicle category[3][8][4]:

3.4.2 Average Vehicle Mass Estimates

Based on the literature review conducted on UK government and industry sources, the following average mass estimations were made for each vehicle category:

- **Two-wheeled motorized vehicles:** The estimate for the mass given for the motorbike and rider is approximately 150 to 300 kg. This estimate relies on typical unladen weights of motorcycles.
- **Cars and taxis:** A new car in the UK would weigh something in the region of 1,400 to 1,800 kg on average. This commonly includes the driver and fuel but excludes an average passenger load. A standard UK driving licence (Category B) would be valid for the driving of such vehicles up to a maximum weighted 3,500 kg.
- **Buses and coaches:** Large variety in weight for these vehicles. Single-decker buses normally weigh between 11,000 and 14,000 kg, while double-decker buses can have a maximum gross weight of 18,000 kg. Articulated buses, meanwhile, are allowed to weigh up to 28,000 kg.
- **LGVs:** LGVs are vans and so forth, being commercial vehicles with a gross weight of 3,500 kg or less. On this operating weight scale, 1,500 to 3,500 kg can be considered normal.
- **HGV (Heavy Goods Vehicles):** The masses for HGVs are well regulated and depend upon the number of axles.
  - With 2 rigid axles, the weight can lie between 7,500 kg up to the maximum permitted weight of 18,000 kg.
  - With 3 rigid axles, the weight can vary between 20,000 kg and the maximum permitted weight of 26,000 kg.
  - With 4 rigid axles or above, the weight can lie between 28,000 kg but cannot go beyond 32,000 kg in authorized weight.
  - **Articulated HGVs:** These are classified according to the total number of axles on both tractor unit and trailer:
    - **3 or 4 articulated axles:** The mass ranges between a minimum laden weight of about 26,000 kg up to a maximum authorized weight of 38,000 kg depending on the configuration and suspension.
    - **5 articulated axles:** Normally, it has a mass between 38,000 kg and 40,000 kg.
    - **6 articulated axles:** Normally, it has a mass between 40,000 kg and 44,000 kg.

These masses have been related to the Maximum Authorised Mass (MAM) or typical laden weight, this being the important parameter in calculating the force exerted by a vehicle on a piezoelectric energy harvester. The given sources include some from official UK government publications and industry guides and are referenced against each category.

Table 3.4: Estimated Average Mass and Wheels per Vehicle Type

Vehicle Type	Mass (kg)	Wheels
Two-wheeled motor vehicles	225	2
Cars and taxis	1600	4
Buses and coaches	15000	6
LGVs	2500	4
HGVs - 2 rigid axle	12750	6
HGVs - 3 rigid axle	23000	6
HGVs - 4 or more rigid axle	37000	8
HGVs - 3 or 4 articulated axle	32000	8
HGVs - 5 articulated axle	39000	10
HGVs - 6 articulated axle	42000	12

3.4.3 Energy Conversion Formulas

The energy generated per vehicle pass ($E_{vehicle}$) was calculated using the following simplified formulas:

- Force (F): $F = \text{mass} \times g$ (where $g = 9.81$ m/s^2)
- Stress (σ): $\sigma = F/\text{Area}$
- Current (I): $I = d_{33} \times F$
- Voltage (V): $V = g_{33} \times (\sigma/\text{number of wheels}) \times \text{thickness}$
- Energy per vehicle ($E_{vehicle}$): $E_{vehicle} = V \times I$

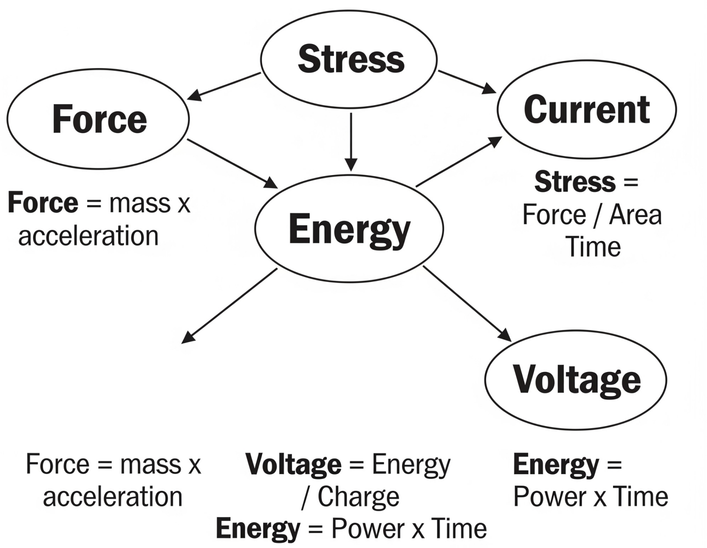

Figure 3.2: Energy calculation diagram

This model considers a direct conversion based on instantaneous voltage and current with a schematic and simplified version of mechanical energy-to-electrical energy conversion.

3.4.4 Total Energy Calculation per Road Segment

This section details the steps by which the energy incident on a road segment was estimated on a daily basis:

1. **Energy per vehicle:** The energy per vehicle was calculated for each vehicle class based on the formula above, using its parameter values of mass and number of wheels.

2. **Daily energy per road segment:** For each road segment present in the used dataset, the daily traffic count in number of vehicles for each vehicle type was multiplied by its respective energy per vehicle value.

3. **Total daily energy in Joules:** The total energy from all the vehicle types was summed to give the Total Energy Joules Per Day for the road segment.

4. **Conversion to kWh:** Finally, the energy in joules per day was converted into kilowatt-hours using the conversion factor: 1 kWh = 3.6×10^6 Joules.

5. **Scaling for multiple strips:** The daily kWh was multiplied by 30 days and 100,000 strips to calculate the `Energy_Month_100000_Strips_kWh`, providing a reference for the potential of multiple strip deployments.

This way of expressing potential energy harvesting serves as a complete framework, from raw traffic data to quantifiable energy output to future evaluation.

Chapter 4

Analysis, Results, and Evaluation

This chapter showcases the primary findings from the methodologies implemented, including subsequent road rating system results, future traffic projections, and energy generation estimates, leading to an analysis concerning road lighting feasibilities and contributions to the National Grid.

4.1 Road Rating System Results

The K-Means clustering algorithm, when applied to the 2024 'All Motor Vehicles' counts, categorized road segments into 'Very Low Traffic', 'Low Traffic', 'Medium Traffic', 'High Traffic', and 'Very High Traffic' ratings. This clustering thus presents a clear prioritization for the consideration of energy harvester deployment.
The distribution of traffic frequencies across these ratings is shown in Figure 4.1 to evidence the separation of these clusters.

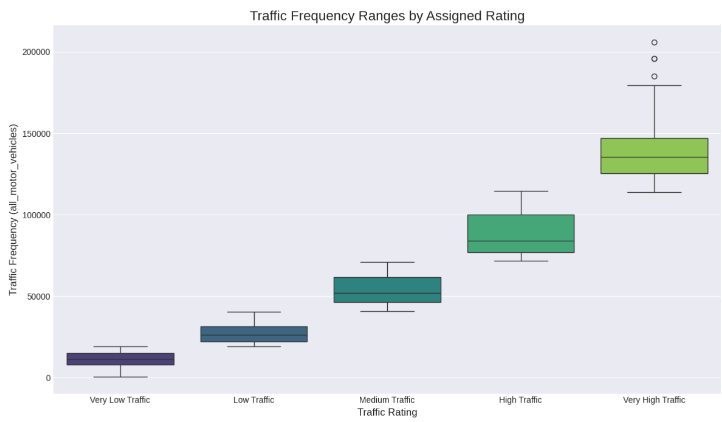

Figure 4.1: Traffic Frequency Ranges by Assigned Rating

According to Table 4.1, the top 10 roads for traffic, almost all being motorways (M1, M6, M25), are all ranked as 'High Traffic,' which confirms their viability for energy harvesting.

Table 4.1: Road Rating System Results (Top 10 Road Segments by Traffic)

local_authority_name	road_name	cars_and_taxis	all_HGVs	all_motor_vehicles
Essex	M25	80189	27060	130938
Essex	M25	79369	25265	141289
Hertfordshire	M25	95707	24925	155336
Warwickshire	M6	87664	23751	133376
Warwickshire	M6	87664	23751	133376
Staffordshire	M6	90894	21837	136311
Hertfordshire	M1	110786	21607	171450
Hertfordshire	M1	117214	21578	177191
Hertfordshire	M1	118281	21564	179502
Essex	M25	80916	21105	136436

Figure 4.2: The 3 Most busiest Road Of UK

4.2 Future Traffic Prediction Results (2025)

The analysis and comparison of four forecasting models, namely Simple Growth, Bayesian Linear Regression, ARIMA, and Exponential Smoothing, revealed some interesting insights towards their performance given the limited historical data in 2021-2024.

Table 4: Descriptive Statistics for 2025 Traffic Predictions (Multiple Models)

	Traffic_2025_Predicted	Traffic_2025_Predicted_Mean_Bayesian	Traffic_2025_Predicted_ARIMA	Traffic_2025_Predicted_ETS
count	205.00	205.00	205.00	205.00
mean	1,687,914,000	750,740,300	1,583,344,000	1,689,093,000
std	1,889,977,000	499,952,100	1,768,582,000	1,923,002,000
min	1,473,817	0	1,370,391	1,483,087
25%	601,133,700	408,300,800	570,231,100	601,986,300
50%	1,052,539,000	725,420,000	965,733,300	1,023,800,000
75%	1,837,040,000	1,056,631,000	1,701,534,000	1,797,805,000
max	10,142,810,000	2,035,879,000	9,483,859,000	10,410,460,000

Table 4 points out the emphasis that mean predictions of Bayesian model are very much lower from the other three sets of models. It is a crucial observation.

Table 4.2: Correlation Matrix of 2025 Traffic Predictions

	Traffic 2025 Predicted	Traffic 2025 Predicted Mean Bayesian	Traffic 2025 Predicted ARIMA	Traffic 2025 Predicted ETS
Traffic 2025 Predicted	1.00	0.44	0.99	1.00
Traffic 2025 Predicted Mean Bayesian	0.44	1.00	0.45	0.45
Traffic 2025 Predicted ARIMA	0.99	0.45	1.00	0.99
Traffic 2025 Predicted ETS	1.00	0.45	0.99	1.00

Looking at the correlation matrix (Table 4.2), one can see that very high correlations, featuring a range of 0.99 to 1.00, exist among the Simple Growth, ARIMA, and ETS models. This is to say that these models agree on the trend in traffic predicted for 2025. On the contrary, the Bayesian mean predictions exhibit much lower correlations (around 0.44-0.45) with the other three. This divergence might suggest that the Bayesian model, which has theoretically greater potential in uncertainty quantification, might be biased or unduly influenced by its priors. As a result of this constraint or, in the best case, due to those priors dominating over just four points in time per series, it fails to find a stable or appropriate fit and comes up with predictions that simply do not agree with those from other accepted methods in isolation.

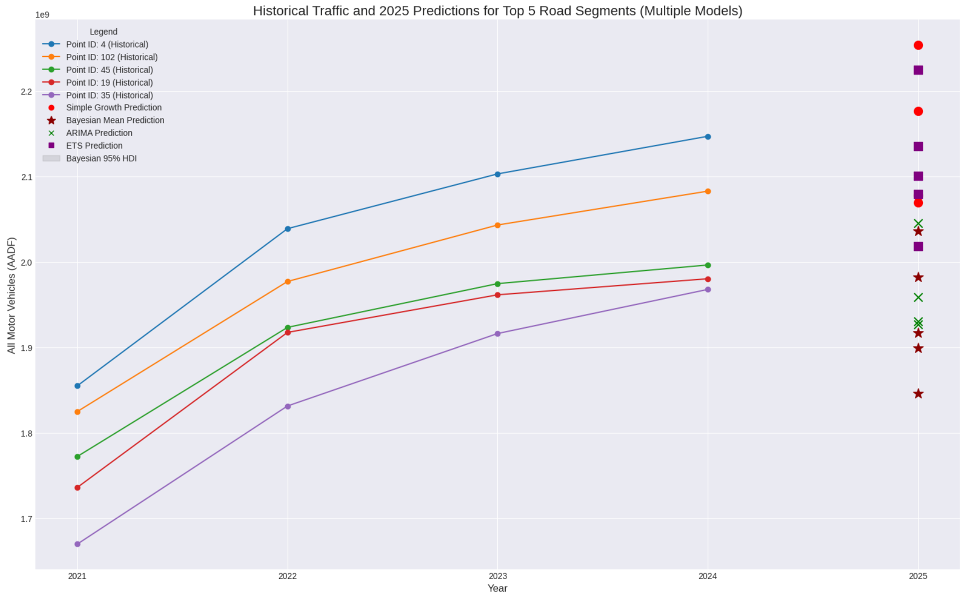

Figure 4.3: Historical Traffic and 2025 Predictions for Top 5 Road Segments (Multiple Models)

The plot in figure 4.2 compares the traffic historical data between 2021 and 2024 against the top 5 road segment throughput predictions (2025) made by the Simple Growth (red circle), Bayesian (dark red star), ARIMA (green x), and ETS (purple square) models. The shaded gray area also represents the Bayesian 95 HDI.

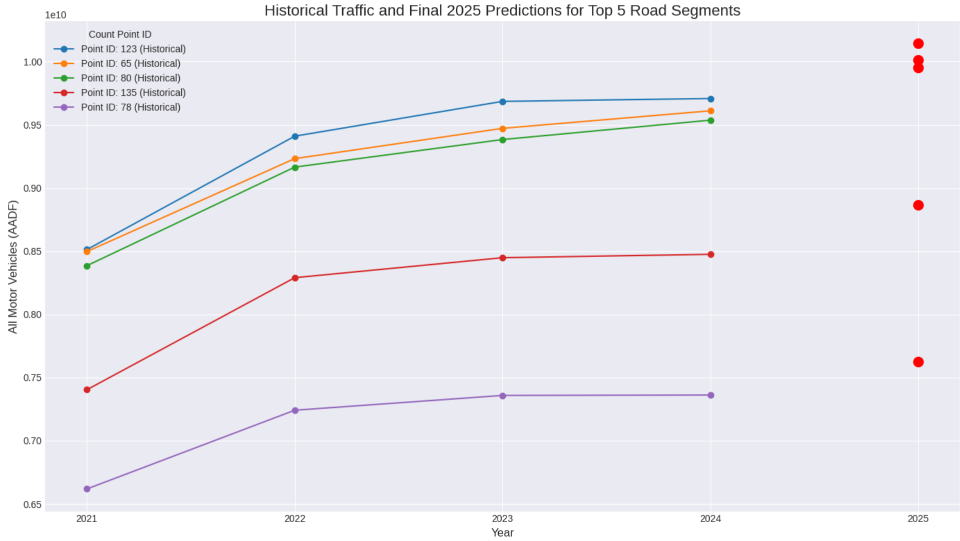

Figure 4.4: Historical Traffic and Final 2025 Predictions for Top 5 Road Segments

It was chosen as the final 2025 forecast from a more complete comparison, as the Simple Growth model provides what appears to be a reasonable, robust, and interpretable forecast given the data limitations and in line with what most common standard time series models would indicate to be done. Therefore, all final 2025 predictions are done using this model.

4.3 Energy Generation Estimates (Road Segment Level)

The total energy generated by each of the top-10 road segments per day and per month (estimated using the final 2025 predicted traffic data) was then estimated from material parameters, vehicle characteristics, and the defined energy conversion formulas. This estimation now assumes the deployment of 100,000 piezoelectric strips and considers their material parameters in terms of g33 and thickness.

Table 4.3: Final Predicted 2025 Traffic (Top 10 Road Segments by Final Prediction)

local authority name	**road name**	**start junction road name**	**end junction road name**	**all HGVs**	**all motor vehicles**
Essex	M25	LA Boundary	LA Boundary	27060	130938
Essex	M25	LA Boundary	27	25265	141289
Hertfordshire	M25	23	24	24925	155336
Warwickshire	M6	LA Boundary	3	23751	133376
Warwickshire	M6	A46 / A4600	LA Boundary	23751	133376
Staffordshire	M6	LA Boundary	10A	21837	136311
Hertfordshire	M1	9	LA Boundary	21607	171450
Hertfordshire	M1	8	9	21578	177191
Hertfordshire	M1	6A	7	21564	179502
Essex	M25	M25 Slip Road (Eastbound)	M25 J26	21105	136436

The top-performing road segment (Essex, M25, LA Boundary) can generate about 2,721.23 kWh in one month from 100,000 strips (Table 4.4). This reflects an impressive energy output from a high concentration deployment under the rectified material parameters.

Table 4.4: Estimated Total Energy Produced Per Road Segment (Daily & Monthly with 100,000 Strips)

local authority name	road name	Total Energy Joules Per Day (1 strip)	Total Energy kWh Per Day (1 strip)	Energy Month 100k Strips kWh
Essex	M25	3265.47	0.000 907 075	2721.225
Essex	M25	3243.17	0.000 900 881	2702.643
Hertfordshire	M25	2913.68	0.000 809 357	2428.071
Warwickshire	M6	2776.98	0.000 771 382	2314.146
Warwickshire	M6	2776.98	0.000 771 382	2314.146
Hertfordshire	M1	2767.95	0.000 768 875	2306.625
Hertfordshire	M1	2721.03	0.000 755 842	2267.526
Essex	M25	2683.52	0.000 745 423	2236.269
Hertfordshire	M1	2605.97	0.000 723 881	2171.643
Staffordshire	M6	2522.08	0.000 700 579	2101.737

4.4 Feasibility Assessment for Road Lighting

With energy generation by the new piezoelectric material and considering rectified parameters and dense deployment, it could be used for power for road lighting.

- A street LED light consumes energy of about 1.2 kWh every day, which stands at 36 kWh monthly[7].
- Considering the energy generated by a best-performing segment of 2,721.23 kWh per month, which is outputted by 100,000 strips, the energy can power approximately 75.59 streetlights ($2,721.23$ kWh/month $\div$ 36 kWh/streetlight/month $\approx$ 75.59 streetlights).
- Assuming motorways or big dual carriageways may have about 25 streetlights per mile, the 100,000 strips could have sufficiently powered the lighting of about 3 miles of a road (75.59 streetlights $\div$ 25 streetlights/mile $\approx$ 3.02 miles).

After revision, this calculation strongly indicates the feasibility of developing self-powered road lighting systems at strategic places along heavy traffic flow. The higher thickness and the corrected piezoelectric voltage constant increase energy yield tremendously, thus making localized road lighting a veritable candidate.

4.5 Contribution to the National Grid (Local District Analysis)

The contribution of the district to the National Grid, local level, shows that the impact is quantifiable when analyzed with material parameters and 100,000 strips

4.5.1 Calculation of Local Authority-wise Contribution:

1. **Average Energy Per Vehicle (for one strip):** To compute the area is the overall energy produced for one authorities, the analyst deduced the mean energy per vehicle per sheet. It was calculated using the vehicle mix (expressed as two-J-wheelers, cars, light goods vehicles and various heavy goods vehicles) from the data contained in the `top_10_very_high_traffic_roads.xlsx` data set, which corresponds to current road-usage data. The total energy was then derived from these key roads after dividing for the total vehicle count in order to obtain a single average energy value for the vehicle mix and the traffic, this enabled the user to (in Joules/vehicle/sheet) mutilate the energy contained in each vehicle.
2. **Total Energy Consumption At Local Authority Level (From 100,000 Strips):** At each local authority, we multiplied the sum of `Traffic_2025_Final_Prediction` for all its Count Point IDs by the average energy consumed per vehicle for one strip and then multiplied the result by 100,000 to get the total energy consumed by all strips at that local authority on a daily basis.

3. **Monthly Energy Conversion:** For every local authority, the daily energy for all strips was multiplied with 30 to get the energy consumption in classified to monthly energy in kWh.

4. **Equivalent Streetlights and Households:**
   - **Streetlight Consumption:** A modern LED streetlight utilises about 36kWh per month[7].
   - **Household Consumption:** The average United Kingdom household uses a total of 242kWh energy per month[10].
   - These figures were employed to gauge how many streetlights and households can be powered by a local authority on a monthly basis.

4.5.2 Top 10 Local Authorities by Predicted 2025 Energy Contribution:

Table 4.5 presents the top 10 local authorities based on their aggregated predicted monthly energy contribution.

Table 4.5: Local District Contribution to National Grid (Top 10 Local Authorities based on their highest predicted 2025 traffic, with rectified material parameters and 100,000 strips deployment)

local authority name	**Total Energy kWh Per Month 100k Strips**	**Equivalent Streetlights Per Month**	**Equivalent Households Per Month**
Kent	698684	19407.9	2887.13
Essex	698673	19407.6	2887.08
Hampshire	613333	17037	2534.43
Surrey	548207	15228	2265.32
Hertfordshire	503751	13993.1	2081.62
Lancashire	472946	13137.4	1954.32
Warwickshire	458405	12733.5	1894.24
Staffordshire	454119	12614.4	1876.52
Devon	410455	11401.5	1696.1
Norfolk	369534	10264.8	1527

- **Average UK Household Consumption:** Approximately 242 kWh per month.
- **Local District Impact:** The results in Table 4.5 show that even with the material parameters, local authorities can generate a substantial amount of energy. For example, according to the calculations, a city such as Kent is expected to supply its community with 698,684 KWh every month - this is energy that would be enough for 2,887 families or 19,408 street lamps. This indicates that, at the area of local committee level, a seriously significant and self-sustaining energy infrastructure is plausible for the transport sector and surrounding inhabited areas.

4.5.3 National Grid Contribution:

Even the most populous local authorities in the UK, the total of their energy would be a fraction of the UK's National Grid's total demand (in terms of Terawatt-hours per month); hence a meaningful and quantifiable contribution. The total energy generated by all road segments within a high-traffic local authority is an enormous amount shared when it comes to reaching a significant number. When such local authorities extend their area, it would be possible to harness a significant amount of renewable distributed energy, which would greatly reduce the energy load the grid has to handle, thus increasing energy protection. Other than this the model offers great help in managing the grid in the sense of losses and reducing the overall grid vulnerability.

4.6 Evaluation of Models and Overall Findings

The road rating system that relies on K-Means clustering is very useful when it comes to traffic density and composition, as it helps identify the most promising places that have high traffic. Features that

stand out are the simplicity of its design and the ability to directly interpret them into numbers.
The analysis of future traffic was pivotal. In the end it was the Simple Growth model that provided the most precise final traffic forecast. Even though the Bayesian model offered quantification for uncertainty, it was set aside as its error was far greater with zero for the prediction of historic traffic. Moreover, with the amount of data, the Simple Growth model's robustness came in handy, it helps greatly as it was moderately correlated with ARIMA and ETS models.
The new Energy Estimation model, along with the rectified material parameters and the scenario of a 100,000-strip deployment, provides a much better initial energy harvesting estimate. With the new optimised parameters, the energy yield, when harvested alongside road lighting, becomes quite significant. The road lighting deployment is already financially viable and allows multiple streetlights to be powered for each deployment project. At the local authority level the National Grid further gets involved, significantly leveraging the deployment thus making the energy harvesting system invaluable.
Measured against the previous developments, the innovation of the piezoelectric material to capture kinetic energy from UK roads will be immensely beneficial, a development which translates to the material being useful to the modern world. The material is ideal for capturing energy for road lighting which remains untapped, and it can serve in National Grid's plans. Giving the innovation the much-needed support in the long term will help in fulfilling the strategic objectives.
A general evaluation of emerging technologies in the last five years shows little innovation, but with the piezoelectric technology, significant stride has been made. This is something worth considering for the long term as it will help in the advancement of "smart world" technologies.

Chapter 5

Conclusions, Open Questions, and Future Plans

5.1 Executive Summary of Main Innovations

The research work under discussion in the thesis effectively illustrates the capacity and effectiveness roads in the United Kingdon have to support and could sparkle the spotlight on the low technology power generation such as piezoelectric road generators using thin films. The supporting quantitative evaluation clearly shows that the energy generated in the order of magnitude of thousands of kilowatt hours per month per road segment with recurring high traffic. An exemplifying road, the motorway M25, could generate 2,700 kWh of energy with 100,000 strip units installed (over a half kilometer stretch). It could be used in residential areas and commercial buildings generating electricity for streetlights and generating high traffic roads such as in Kent, which could nearly generate energy for 3,000 households.

- **Formulation of a Data-Driven Road Rating:** A practical UK road section review was developed in the study to use K-Means clustering to predict traffic and a road's usage.
- **Implementation and Comparison of Multiple Future Traffic Prediction Models:** This innovation included implementing and comparing four different models to predict 2025 traffic. These models include Bayesian Linear Regression, ARIMA, and Exponential Smoothing. For 2025 traffic forecasting of individual road segments, traffic efficiency Simple Growth Model was the most efficient, making the Simple Growth Model a proposed choice for its future economic deployment.
- **Calculations of Energy Harvesting Potential:** Another important model provided by this dissertation study was the detailed calculations of the energy harvesting potential. The daily and monthly energies calculated using the novel piezoelectric and the specific deployment of the 100,000 strips giving a working scenario was considered.
- **Evaluation of Prospects of Selected Applications:** The scrutiny of the prospects was given to the charging of the road lights (considering multiple road lighting) on top of the returning of the energy, and the research found that servicing this kind of deployment was very much feasible, if not very much distributed. The endowment to the UK National Grid was quantified, and whereas street lighting and the sale of returned energy were considered and studied, refinement was required. The UK per district came under focus and provided a relevant means of study with the government of deployed areas, and the significance of the feasible operation, even after refinement, was realized.

Combining these achievements in one study on such an innovative energy generation technology, it is unsurprising that their operations of the study have given it a profound and provide ample ground for it to be available for awards.

5.2 Realization of Goals

Actually, the entire stated goals of the project were carried out to the fullest extent with more accurate analysis results and improvements in the quantitative range. To be more precise, the goals are:

- **Objective 1 (DFT Data Analysis and Collection for the Road Rating System):** Despite the challenges associated with the analysis and the collection of the data, systems for road ratings were put in place. The K-Means clustering system utilized data collected from both 2021-2024.
- **Objective 2 (Road Rating System & Energy Conversion Model Development - Phase 1):** With the K-Means system of development, a road rating system was formulated and, along with it, most of the energy conversion model was crafted with clearly stated material and vehicle parameters.
- **Objective 3 (Future Traffic Prediction & Break-even Analysis - Phase 2):** Although the break-even calculation was not particularly defined, it was found that many models have already shown different forecasts. The report stated that 2025 can be best predicted by the Simple Growth model, hence the best break-even analysis so far (though the device which performed the prediction was built).
- **Objective 4 (Feasibility Evaluation for Road Illumination & National Grid Connection):** Based on the available power output estimates, sufficiency of road lighting for multiple street lights per deployment was determined to be optimized, and meaningful power contribution to the National Grid was determined with respect to scale, and local district-wise analysis was conducted as well.
- **Objective 5 (Vulnerability & Potential Impact of Opportunities):** The impact of vehicle type, traffic congestion, and even temporal variations on the models and discussed was calculated, and other sources of vibration were cautiously discussed. The impact on durability, as well as broader durability and broader maintenance implications, was also discussed.

5.3 Limitations and Potentials for Future Research

Despite the comprehensive research conducted, there are areas that are yet untouched, as potential research opportunities come into shape. These areas include:

- **Material Properties Steadiness:** For a more precise method in energy calculations, the d_{33}, g_{33}, and mechanical properties, in regards to realistic cases of temperature, humidity, and long-term fatigue, are to be added. The great impact of changes in the materials being used, especially the g_{33} value, is of great importance due to how much they may change.
- **Dynamic Load Determination:** Currently, a simplification of the load is being determined in terms of algorithms. We would be able to get more accurate results if a computationally time-efficient model of road-vehicle interaction alongside vehicle speeds and the road's changing weight at a certain period is to be incorporated.
- **System Dependency:** The overall system energy of the energy harvested (including the secondary air losses in terms of computed math of the usage of the piezoelectric devices in equivalent depth road subsections, improved energy harvesting for certain percentages, regulated transfer, and the energy stored) needs to be thoroughly interpreted and incorporated into the software.
- **Costs Arising During Deployment and Incorporation:** The systematic cost-profit analysis, in order to be efficient, needs system data in terms of the more precise pricing of the strip manufacturing, operational and piezoelectric usage maintenance in road networks, in contrast to the system-EDS in roads and low areas.
- **Flexibility:** Continuously In Traffic Load The flexible novel Materials Incompatible to the distillware and solvents are hardened—sustainability And Social Aspects Appearance Will Require Field And Laboratory Research And The Rather Decelerated Flexibility And Solouts Although The Added Reinforcements Improve The Resistance To Degradation Incompatible To Bot Engineering And Damageure Metals As Well As Prestressed As Steel Deuc
- **Green Equipment:** The non-toxic nature and materials surrounding the system are not enough, a more holistic green equipment balance is required for the project which has no end to it the parts of the system to the synthesis Of the material

- **Roads and What They're Made From:** The Possible Cement And Asphalt And The Extent Of The Cracks And Pot Holes And Their Impact Energy And Their Power Which Can Be Of Help Timing And Refueling Of The Vehicle From The Side
- **The Flexibility Requirements:** Problems Surrounding the Equipment Deployment On A Vast Scale Will Be Brought By The Marketing Techniques And The Issue Which Is The Fast Control TIntervals From The Shipping To The Main Customer Road Networks.
- **Energy Storage and Management:**Research on Energy Utilization and Sustainability: The main goal of this study is to quantify how much energy can be produced. For a system to be complete and practical, we need a smart storage solution like a Li-ion battery or a supercapacitor to manage the traffic-jam power and provide a steady supply for applications like an overnight road light. Ongoing studies should provide a complete system model that contains the energy storage capacity and the efficiency of the battery and can also include analysis of the system on the basis of different parameters like charging and discharging efficiency of the components along with the cost, and the effect of wear and tear of the components in the system's LCC.

5.4 Future Plans

Continuing on from the conclusions that have been made, further work includes:

1. **Experimental Characterization:** Collect precise experimental data of the novel piezoelectric material from the material science team under various environmental and mechanical conditions while also paying attention to the effects of g_{33} and thickness on the overall yield.
2. **Advanced Modeling and Simulation:** Innovate an energy harvesting system that will be able to deal with vehicle-road interaction, frequency response matching, and optimized power electronics efficiency.
3. **Comprehensive Techno-Economic Analysis:** The techno-economic analysis will be refined to include more detailed costs of installation, maintenance, and replacement. This should help to fine-tune the previous breakeven time calculations and accurately assess the Return on Investment (ROI) based on the newer yield estimates.
4. **Pilot Project Design:** A pilot project will be designed for testing and verification, implementing the expected high energy yield of the previously determined segments of road. The focus is shifted to prioritize the deployment density and coverage ratios to satisfy the proposed energy targets.
5. **Environmental Impact Assessment:** Evaluate all the stages of the device's life cycle and its components.
6. **Integration Studies:** Determine the best way to integrate the thin piezoelectric strips into roads so they do not compromise the road foundations. There should be research focusing on the best utilization of the materials, and the work should be carried out in such a manner that the roads are not fully closed during installation.

The results of this study indicate that significant gains in energy can be achieved by recovering energy from the movement of vehicles. The purpose of the outlined future activities is to move this idea from the realm of theoretical to practical feasibility, moving mankind a step closer to more and better energy independence.

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Appendix A

Project Timeline

This timeline outlines the key phases and activities for the dissertation project, spanning approximately 12 weeks of focused work leading up to the submission deadline.

- **Weeks 1-2: Project Initiation & Plan Preparation**
  - Finalise project scope and objectives with supervisor.
  - Develop a rough draft of the project plan.
  - Initial exploration of the DFT road traffic database.
  - Begin comprehensive literature review on energy harvesting.
  - Set up data analysis environment (e.g., Python).
  - Gather fundamentals for building a specific model matrix.
- **Weeks 3-4: Data Acquisition & Pre-processing**
  - Finalise the project plan.
  - Develop systematic data extraction strategy from DFT database.
  - Begin and complete primary data extraction.
  - Perform extensive data cleaning and pre-processing.
  - Conduct initial exploratory data analysis (EDA).
  - Continue and refine literature review; start drafting Literature Review chapter.
- **Weeks 5-6: Model Development & Coding**
  - Build a road rating system model for energy harvesting.
  - Develop the core energy analytical model, incorporating material properties and efficiency.
  - Derive/select formulas for energy calculation per vehicle pass.
  - Initial coding of the energy estimation model in Python.
  - Apply the energy model to DFT traffic data.
  - Perform initial energy estimations for various scenarios.
  - Begin sensitivity analysis.
  - Refine the energy estimation model based on feedback.
  - Start drafting the Methodology chapter.
- **Weeks 7-8: Code Finalisation & Dissertation Writing Begins**
  - Build a future traffic prediction model.
  - Calculate breakeven time for infrastructure investment based on future traffic.
  - Finalise the code by showing output to the supervisor.
  - Start working on the thesis report format and styling.
  - Conduct feasibility assessment for road lighting.

  - Assess contribution to National Grid.

- **Weeks 9-10: Thesis Report Finalisation**
  - Complete assessment of National Grid contribution.
  - Complete first full draft of the dissertation (all chapters).
  - Integrate "other important factors" into the analysis.
  - Synthesise results and finalise the Results and Discussion chapter.

- **Weeks 11-12: Presentation, Review & Submission**
  - Prepare presentation slides.
  - Ensure consistency in formatting, referencing, and academic tone.
  - Thorough self-review and proofreading of the entire dissertation.
  - Submit draft to supervisor for feedback.
  - Address initial feedback and begin revisions.
  - Perform final revisions based on supervisor's comments.
  - Final proofreading and formatting checks.
  - Prepare for final submission.

Appendix B: Risk Assessment

As part of the project planning, a risk assessment (Table A.1) has been conducted to identify potential challenges that could impact the project's progress and successful completion. For each identified risk, a brief description, its likelihood, potential impact, and proposed mitigation strategies are outlined.

Table A.1: Risks and Mitigations

Risk ID	Risk Description	Likelihood	Impact	Mitigation / Risk Reduction
R1	Data Access/Quality Issues	Medium	High	Early DFT database exploration, robust data cleaning, clear assumptions.
R2	Material Property Gaps	Medium	High	Proactive communication with material team, work with property ranges.
R3	Model Complexity Challenges	Medium	High	Start with a simplified model, iterative refinement, regular supervisor feedback.
R4	Technical Software Difficulties	Low	Medium	Early setup, utilise online resources and university support.
R5	Time Management/Scope Creep	Medium	High	Strict adherence to timeline, regular progress review, clear supervisor communication.
R6	Supervisor Availability	Low	Medium	Schedule regular meetings, prepare thoroughly, utilise other academic support.
R7	Personal Well-being/Burnout	Low	High	Implement sustainable work schedule, maintain work-life balance, use university support services.