INTERNAL COMBUSTION ENGINE

CEP REPORT

Title:

Enviro-Economic Assessment of Alternative Fuels in Engine Performance and Emissions

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Abstract

The rising global energy demand and environmental concerns have driven the adoption of alternative fuels in internal combustion engines. This study presents a comprehensive enviro-economic assessment of two alternative fuels, Fuel P and Fuel Q, in terms of engine performance, CO_2 emissions, and associated economic costs. The analysis integrates modern computational and analytical tools: report formatting and professional presentation using LaTeX, graphical visualization with Origin Pro, statistical optimization using Minitab, and the Caliskan method for calculating annual CO_2 emissions and enviro-economic costs. Normalization techniques and the Enviro-Economic Index (EEI) were applied to identify optimal operating conditions for engine efficiency, environmental performance, and economic feasibility. Furthermore, a sector-specific carbon taxation policy for power plants and automobiles was developed based on the modeled CO_2 emissions, incentivizing operation at RPMs that minimize environmental and economic impact. Results highlight the optimal engine RPM range and provide recommendations for sustainable fuel utilization, demonstrating the integration of modern analytical tools to guide policy and operational decisions in Pakistan's transport and energy sectors.

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Introduction

1.1 Background

The rapid growth of anthropogenic activities, including industrialization, urbanization, and transportation expansion, has intensified global environmental degradation. Developing countries such as Pakistan rely heavily on fossil-fuel–based energy systems, particularly in the transport sector, to support economic growth and mobility demands. This reliance has increased petroleum consumption, resulting in elevated greenhouse gas emissions and significant pressure on national energy resources.

The transport sector is a major contributor to carbon dioxide (CO_2) emissions due to the widespread use of internal combustion engine vehicles fueled by gasoline and diesel. In Pakistan, transportation accounts for a substantial share of oil consumption, thereby amplifying CO_2 emissions and worsening urban air quality. Alongside CO_2, vehicular exhaust releases carbon monoxide, unburned hydrocarbons, nitrogen oxides, sulfur oxides, and particulate matter, all of which pose serious risks to public health and environmental sustainability.

The growing vehicle population and projected increase in road transport activity are expected to further elevate emission levels if current practices persist. This escalation threatens not only environmental quality but also economic stability through increased healthcare costs, energy imports, and climate-related impacts. Despite the urgent need to reduce emissions, an abrupt transition away from fossil fuels is economically impractical for developing economies.

Consequently, the adoption of sustainable and transitional transportation solutions, such as improved engine technologies, alternative fuels, and hybrid systems, is essential to balance environmental protection with economic feasibility. An enviro-economic evaluation of these alternatives provides a systematic framework to assess emission reduction potential, cost effectiveness, and long-term sustainability. This study focuses on analysing the environmental and economic impacts of alternative transportation fuels in Pakistan, aiming to support informed decision-making for sustainable transport development.

https://www.sciencedirect.com/science/article/pii/S2405844024098177

1.2 Problem Statement

The **power and automobile** sectors in Pakistan contribute significantly to **environmental pollution**. There is a need to evaluate alternative fuels based on both **environmental and economic performance**. This study aims to assess two alternative fuels using **enviro-economic analysis** and **optimization techniques** to determine optimal operating conditions and recommend sustainable solutions.

1.3 Objectives

The main objectives of this study are:

- To perform enviro-economic analysis using the Caliskan method.
- To optimize engine operating conditions for maximum power and minimum CO_2 emissions.
- To evaluate carbon pricing and propose an emission-based taxation policy.
- To recommend the most suitable fuel for practical application in Pakistan.

Literature Review

2.1 Alternative Fuels and Emission Characteristics

Alternative fuels such as **LPG, CNG,** and **alcohol blends** have been studied extensively to assess their performance and emission characteristics in internal combustion engines. **LPG-powered SI engines** have shown measurable reductions in carbon dioxide emissions when evaluated using engine power and emissions data, providing a basis for environmental cost calculation.
Comparative studies of **gasoline blended** with **heptanol or hexanol** indicate that fuel composition directly affects emissions and environmental impact. **Gasoline** with **higher alcohol blends** tends to emit more **CO_2**, increasing the associated environmental cost, while alternative fuels such as LPG and CNG offer cleaner combustion and lower emission profiles.
The adoption of alternative fuels not only reduces CO_2 and other harmful **exhaust emissions**, including **CO, unburned hydrocarbons, NO_x, and particulate matter**, but also provides an economic pathway through the concept of **carbon taxation**. By imposing higher tax costs on high-emission fuels such as gasoline, consumers are encouraged to shift towards cleaner fuels, promoting sustainable energy use. Experimental studies at varying engine speeds allow a detailed understanding of the relationship between fuel type, engine performance, emissions, and economic implications. This integrated enviro-economic approach highlights the potential of alternative fuels in reducing environmental damage while supporting sustainable transport strategies. https://www.sciencedirect.com/science/article/pii/S2405844024098177

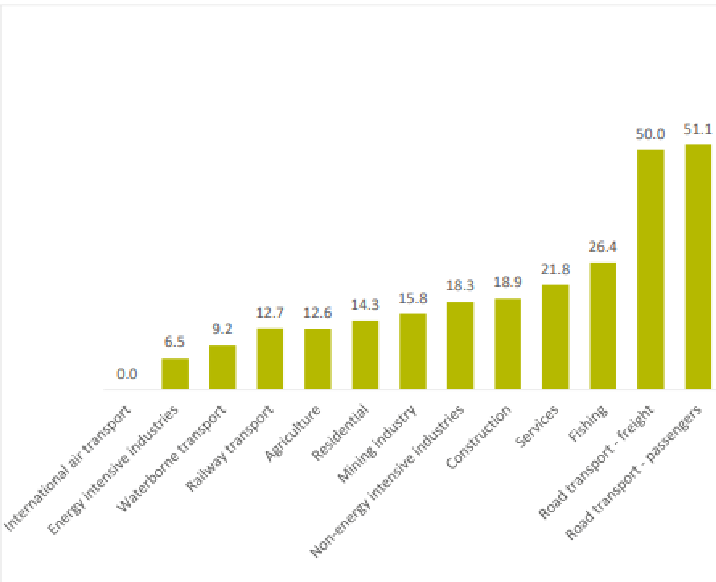
2.2 Enviro-Economic Analysis

The world faces the dual challenge of fossil fuel depletion and environmental degradation. Excessive extraction and consumption of petroleum-based fuels have not only reduced underground carbon resources but also contributed to greenhouse gas emissions, climate change, acid rain, and ozone depletion. Countries lacking crude oil reserves, such as India and Pakistan, spend significant amounts on imports, creating economic burdens. For instance, India imports 70% of its petroleum needs, costing billions annually, highlighting the economic incentive to adopt alternative fuels such as bio-diesel, LPG, CNG, and ethanol.
Environmental concerns, particularly after the Earth Summit '92, have prompted global efforts to reduce emissions, including the Kyoto Protocol and SDG targets. The transport and agricultural sectors are major consumers of fossil fuels and significant contributors to CO_2 emissions. Alternative fuels offer potential solutions, reducing environmental impacts while supporting energy security and sustainability.
From a performance perspective, gasoline exhibits high volumetric efficiency and engine power due to its favorable air-fuel ratio and heat of vaporization. Alternative fuels such as methanol, ethanol, hydrogen, and methane generally produce lower power and higher brake-specific fuel consumption, although they offer higher octane numbers, which can improve engine performance if engines are optimized for these fuels. Emission characteristics vary, with gasoline producing higher CO and CO_2 emissions, while gaseous and alcohol-based fuels generate comparatively lower harmful exhaust components.
The enviro-economic approach evaluates both performance and environmental costs. By asso-

ciating fuel emissions with carbon pricing or taxation, high-emission fuels can be economically discouraged, promoting cleaner alternatives. This strategy supports sustainable transport, reduces environmental damage, and aligns with long-term energy and climate goals.
https://www.researchgate.net/publication/263874565 Review of fuels for internal combustion engines in the aspect of economy performance environment and sustainability

2.3 Carbon Pricing and Environmental Taxation

Carbon pricing has been adopted globally as an effective policy tool to internalize environmental costs. It encourages the adoption of cleaner technologies and fuels by imposing a financial penalty on carbon emissions.
Carbon pricing and energy taxation are key tools to promote cleaner energy use and reduce greenhouse gas emissions. By assigning a monetary cost to carbon emissions, these measures ensure that polluters pay for the societal and environmental impacts of their energy consumption. Carbon pricing can be implemented through explicit carbon taxes, excise duties, or emission trading systems, such as the European Union Emission Trading System (EU ETS), which caps emissions in electricity, heat generation, energy-intensive industries, and aviation.
Explicit carbon taxes have become increasingly common and vary widely between regions, with higher rates incentivize greater emission reductions. By putting a price on CO_2 emissions, these taxes encourage the adoption of low-carbon technologies and fuels, aligning energy use with climate objectives. Energy taxation also has economic implications for households, as energy expenditures vary across income groups. To improve public acceptance, revenue from carbon taxes can be transparently earmarked for environmental projects, redistributed to reduce other taxes, or used to support vulnerable populations.
Overall, carbon pricing and environmental taxation serve a dual purpose: they provide economic signals to reduce emissions while generating resources that can support sustainable development. When effectively implemented, these instruments help transition societies toward cleaner energy, lower carbon footprints, and climate resilience.



Source: ECA based on Trinomics, *Study on Energy costs, taxes and the impact of government interventions on investments - Final Report Energy Taxes*, October 2020, p. 22.

Figure 2.1: Average energy tax of different sectors

https://www.eca.europa.eu/lists/ecadocuments/rw22 01/rw energy taxation en.pdf

Methodology

3.1 Experimental Data Description

The engine performance data for two alternative fuels, **Fuel P** and **Fuel Q**, is collected over a range of engine speeds from 1600 to 4400 RPM. The dataset includes the **brake power output** of the engine and the corresponding **CO_2 emissions** in grams per kilowatt-hour (g/kWh). This information forms the basis for the **enviro-economic analysis** and subsequent optimization to determine optimal operating conditions for power generation with minimal environmental impact. The data was structured as shown in Table 3.1. This dataset enables the comparison of the performance of the two fuels and provides input for calculating the **annual CO_2 emissions** and **carbon cost** per vehicle.

Table 3.1: Engine performance data for Fuels P and Q at various RPMs

RPM	P (kW)	Q (kW)	P CO_2 (g/kWh)	Q CO_2 (g/kWh)
1600	0.864166	0.775103	482.372	387.167
2000	1.383308	1.210847	437.943	342.738
2400	2.041199	1.845139	387.167	330.044
2800	2.839004	2.720655	431.596	355.432
3200	3.651537	3.193355	456.984	374.473
3600	4.561962	3.702889	488.719	412.555
4000	5.430333	4.410318	558.536	469.678
4400	5.266979	4.415778	628.353	558.536

3.2 Methodology Interpretation

To provide a structured overview of the research methodology, the study follows a systematic workflow. The steps include collection of engine performance and emission data for Fuels P and Q, calculation of annual CO_2 emissions using the Caliskan method, statistical optimization of engine operating conditions in Minitab, and evaluation of carbon pricing for each fuel across various RPM levels. This approach ensures a comprehensive assessment of enviro-economic performance, guiding optimal fuel selection and operational strategies.

3.3 Caliskan Enviro-Economic Analysis Framework

3.3.1 Annual CO_2 Emissions Calculation

The annual carbon dioxide (CO_2) emissions of an automobile were estimated using the enviro-economic framework proposed by Caliskan, combined with the operational characteristics of the engine. The analysis assumes that the vehicle operates for **8 hours per day** throughout the year, corresponding to **365 operating days**. Based on this operating profile, the annual CO_2 emissions were calculated as follows:

$$x_{\mathrm{CO_2}} = y_{\mathrm{CO_2}} \times W_{\mathrm{gen}} \times t_{\mathrm{working}} \tag{3.1}$$

where,

- $x_{\mathrm{CO_2}}$ is the annual carbon dioxide emissions (kg/year),
- $y_{\mathrm{CO_2}}$ is the specific CO_2 emission factor (g/kWh),
- W_{gen} is the generated engine power (kW),
- t_{working} is the annual engine operating time (hours/year).

The annual engine operating time was taken as $t_{\mathrm{working}} = 2920$ h, which corresponds to an average daily operation of 8 h over the entire year.

The enviro-economic cost associated with CO_2 emissions was calculated using the following relation:

$$C_{\mathrm{CO_2}} = c_{\mathrm{CO_2}} \times x_{\mathrm{CO_2}} \tag{3.2}$$

where,

- $C_{\mathrm{CO_2}}$ represents the enviro-economic cost of CO_2 emissions (USD/year),
- $c_{\mathrm{CO_2}}$ is the unit price of CO_2 emissions (USD/tCO_2),
- $x_{\mathrm{CO_2}}$ is the annual CO_2 emissions (t/year).

Carbon prices vary significantly across countries as a policy instrument to mitigate CO_2 emissions. Among these, several European countries have established standardized carbon pricing mechanisms. In the present investigation, the Swiss carbon price is adopted for the estimation of carbon emission costs due to its consistency and applicability in enviro-economic assessments. The unit cost of carbon emissions is taken as **8.28 USD $\mathbf{tCO_2^{-1}}$**, which is used to calculate the annual carbon cost corresponding to the estimated CO_2 emissions at different engine operating conditions.

The combined enviro-economic performance of fuels **P** and **Q** is summarized in the following table. The comparison is carried out over a wide range of engine speeds to evaluate the variation in power output, specific CO_2 emissions, annual CO_2 generation, and corresponding carbon emission costs. For each operating condition, the annual CO_2 emissions are estimated using the **Caliskan framework**, assuming a constant annual engine operating time. The carbon emission cost is then calculated using a uniform carbon price to ensure a consistent and unbiased comparison between the two fuels. This combined assessment provides a comprehensive basis for evaluating the environmental and economic implications of liquid and gaseous fuel usage in internal combustion engines.

Table 3.2: RPM-wise Power, CO_2 Emissions, and Annual Cost for Fuel P and Fuel Q

RPM	$\mathbf{P_P}$ **(kW)**	$\mathbf{P_Q}$ **(kW)**	$\mathbf{CO_{2,P}}$ **(g/kWh)**	$\mathbf{CO_{2,Q}}$ **(g/kWh)**	$\mathbf{CO_{2,P}}$ **(ton/yr)**	$\mathbf{CO_{2,Q}}$ **(ton/yr)**	$\mathbf{Cost}_P$ **(USD/yr)**	$\mathbf{Cost}_Q$ **(USD/yr)**
1600	0.864	0.775	482.372	387.167	1.217	0.876	10.08	7.26
2000	1.383	1.211	437.943	342.738	1.769	1.212	14.65	10.03
2400	2.041	1.845	387.167	330.044	2.308	1.778	19.11	14.72
2800	2.839	2.721	431.596	355.432	3.578	2.824	29.62	23.38
3200	3.652	3.193	456.984	374.473	4.873	3.492	40.35	28.91
3600	4.562	3.703	488.719	412.555	6.510	4.461	53.90	36.93
4000	5.430	4.410	558.536	469.678	8.856	6.049	73.33	50.08
4400	5.267	4.416	628.353	558.536	9.664	7.202	80.02	59.63

3.4 Enviro-Economic Analysis and EEI Evaluation

3.4.1 Normalization Formulas

To standardize engine performance, emissions, and cost for comparison across RPMs, the following normalization formulas were applied:

$$P_{\text{norm}} = \frac{P_i - P_{\text{min}}}{P_{\text{max}} - P_{\text{min}}} \tag{3.3}$$

$$CO_{2,\text{norm}} = \frac{CO_{2,i} - CO_{2,\text{min}}}{CO_{2,\text{max}} - CO_{2,\text{min}}} \tag{3.4}$$

$$Cost_{\text{norm}} = \frac{Cost_i - Cost_{\text{min}}}{Cost_{\text{max}} - Cost_{\text{min}}} \tag{3.5}$$

where P_i, $CO_{2,i}$, and $Cost_i$ are the values at a specific RPM, and min/max values are the minimum and maximum observed across all RPMs for the respective fuel.

3.4.2 Enviro-Economic Index (EEI)

The Enviro-Economic Index (EEI) is a composite parameter used to evaluate the overall performance of fuels by considering engine power, emissions, and cost. In this study, the EEI has been modified to include the carbon emission cost as an economic factor, in addition to normalized power and CO_2 emissions. The weights are assigned based on the relative importance of each factor: 0.4 for power, 0.4 for CO_2 emissions, and 0.2 for cost. A higher EEI value indicates better overall performance considering both environmental and economic aspects. The Enviro-Economic Index (EEI) integrates normalized power, CO_2 emissions, and cost with assigned weights to evaluate overall engine efficiency:

$$EEI = 0.4\,P_{\text{norm}} + 0.4\,CO_{2,\text{norm}} + 0.2\,Cost_{\text{norm}} \tag{3.6}$$

Higher EEI values indicate better performance when considering a balance between power output, environmental impact, and economic cost.

Table 3.3: RPM-wise Power, CO_2 Emissions, Cost, and EEI for Fuel P

RPM	P_P	$\mathbf{CO}_{2,P}$	$\mathbf{Cost}_P$	$P_{\text{norm,P}}$	$CO_{2,\text{norm,P}}$	$\mathbf{Cost}_{\text{norm,P}}$	$\mathbf{EEI}_P$
Unit	kW	g/kWh	USD/year	-	-	-	-
1600	0.864	482.372	10.08	0	0.605	1	0.442
2000	1.383	437.943	14.65	0.114	0.789	0.935	0.548
2400	2.041	387.167	19.11	0.258	1	0.871	0.677
2800	2.839	431.596	29.62	0.432	0.816	0.721	0.643
3200	3.652	456.984	40.35	0.610	0.711	0.567	0.642
3600	4.562	488.719	53.90	0.810	0.579	0.373	0.630
4000	5.430	558.536	73.33	1	0.289	0.096	0.535
4400	5.267	628.353	80.02	0.964	0	0	0.386

Table 3.4: RPM-wise Power, CO_2 Emissions, Cost, and EEI for Fuel Q

RPM	P_Q	$\mathbf{CO}_{2,Q}$	$\mathbf{Cost}_Q$	$P_{\text{norm,Q}}$	$CO_{2,\text{norm,Q}}$	$\mathbf{Cost}_{\text{norm,Q}}$	$\mathbf{EEI}_Q$
Unit	kW	g/kWh	USD/year	-	-	-	-
1600	0.775	387.167	7.26	0	0.750	1	0.500
2000	1.211	342.738	10.03	0.120	0.944	0.947	0.615
2400	1.845	330.044	14.72	0.294	1	0.857	0.689
2800	2.721	355.432	23.38	0.534	0.889	0.692	0.708
3200	3.193	374.473	28.91	0.664	0.806	0.587	0.705
3600	3.703	412.555	36.93	0.804	0.639	0.433	0.664
4000	4.410	469.678	50.08	0.998	0.389	0.182	0.591
4400	4.416	558.536	59.63	1	0	0	0.400

3.4.3 Observations and Remarks

The EEI evaluation shows that for Fuel P, the optimal RPM is 2400, achieving the highest EEI (0.677), representing the best balance between engine power, CO_2 emissions, and cost.
For Fuel Q, the highest EEI (0.708) occurs at 2800 RPM, indicating that Fuel Q performs most efficiently slightly above the optimal RPM of Fuel P.
At higher engine speeds (4000-4400 RPM), EEI decreases for both fuels due to elevated emissions and costs despite higher power output. This highlights the trade-off between performance, environmental impact, and economic considerations. The analysis was performed in Minitab and exported to Excel for the calculation of normalized parameters and EEI for both fuels.

3.4.4 Mini Tab Snapshots

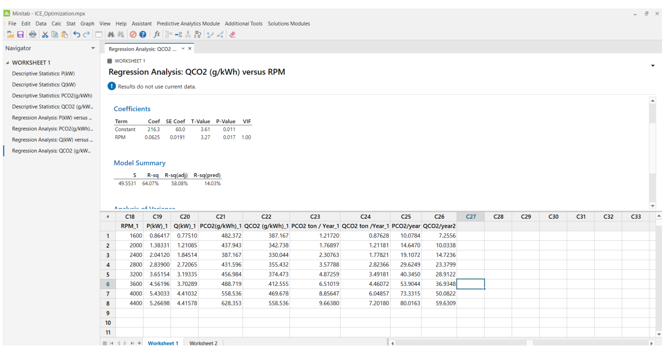


Figure 3.1: Data Input

WORKSHEET 1

Regression Analysis: PCO2(g/kWh) versus RPM

Results do not use current data.

Regression Equation

PCO2(g/kWh) = 309.4 + 0.0582 RPM

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	309.4	67.5	4.59	0.004	
RPM	0.0582	0.0215	2.71	0.035	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
55.7449	54.96%	47.45%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	22747	22747	7.32	0.035
RPM	1	22747	22747	7.32	0.035
Error	6	18645	3107		
Total	7	41392			

Figure 3.2: Regression of RPM Vs CO_2

Regression Analysis: P(kW) versus RPM

Results do not use current data.

Regression Equation

P(kW) = -2.051 + 0.001769 RPM

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-2.051	0.345	-5.94	0.001	
RPM	0.001769	0.000110	16.08	0.000	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.285220	97.73%	97.35%	94.79%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	21.0231	21.0231	258.43	0.000
RPM	1	21.0231	21.0231	258.43	0.000
Error	6	0.4881	0.0814		
Total	7	21.5112			

Fits and Diagnostics for Unusual Observations

Obs	P(kW)	Fit	Resid	Std Resid
8	5.267	5.731	-0.464	-2.13 R

R Large residual

Figure 3.3: Regression of RPM vs Power

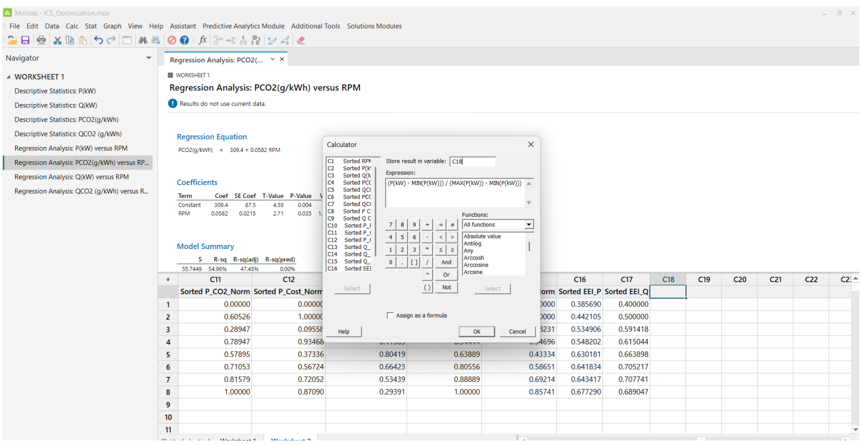


Figure 3.4: Normalization Formulas

C10	C11	C12	C13	C14	C15
Sorted P_POWER_NORM	Sorted P_CO2_Norm	Sorted P_Cost_Norm	Sorted Q_Power_Norm	Sorted Q_CO2_Norm	Sorted Q_Cost_Norm
0.96423	0.00000	0.00000	1.00000	0.00000	0.00000
0.00000	0.60526	1.00000	0.00000	0.75000	1.00000
1.00000	0.28947	0.09558	0.99850	0.38889	0.18231
0.11369	0.78947	0.93468	0.11969	0.94444	0.94696
0.80982	0.57895	0.37336	0.80419	0.63889	0.43334
0.61044	0.71053	0.56724	0.66423	0.80556	0.58651
0.43249	0.81579	0.72052	0.53439	0.88889	0.69214
0.25777	1.00000	0.87090	0.29391	1.00000	0.85741

Figure 3.5: Normalized Values of Power, Cost, Emissions for P and Q Fuel

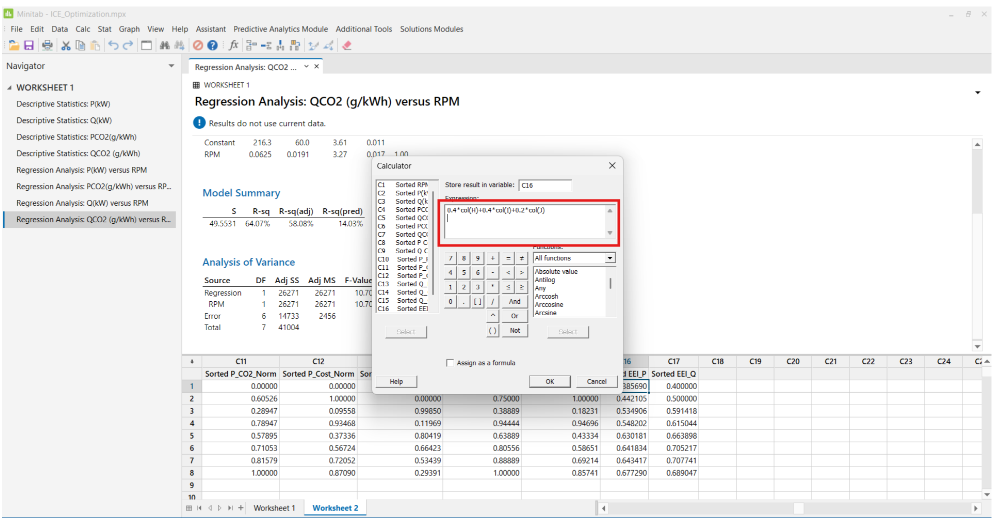


Figure 3.6: Optimization Equation

Modelling and Taxation Policy

4.1 Power Plant Sector: CO_2 Emission Modeling

4.1.1 Modeling Equations

The annual CO_2 emissions from a power-generating engine operating at a fixed RPM can be calculated as:

$$x_{\mathrm{CO_2}} = y_{\mathrm{CO_2}} \times W_{\mathrm{gen}} \times t_{\mathrm{working}} \tag{4.1}$$

$$C_{\mathrm{CO_2}} = c_{\mathrm{CO_2}} \times x_{\mathrm{CO_2}} \tag{4.2}$$

where:

- $x_{\mathrm{CO_2}}$: Annual CO_2 emissions (kg/year)
- $y_{\mathrm{CO_2}}$: Specific CO_2 emission factor (g/kWh)
- W_{gen} : Engine power output (kW)
- t_{working} : Annual operating hours (hours/year)
- $C_{\mathrm{CO_2}}$: Annual carbon cost (USD/year)
- $c_{\mathrm{CO_2}}$: Price of CO_2 per ton (USD/tCO_2)

4.1.2 Taxation Policy for Power Plant Sector

Based on this model:

- **Assumption:** Engine operates 8 hours/day, 365 days/year.
- **Annual Emission Calculation:** Use the optimum RPM identified from EEI analysis (e.g., 2400 RPM for Fuel P or 2800 RPM for Fuel Q) to compute $x_{\mathrm{CO_2}}$.
- **Carbon Tax:** Apply $c_{\mathrm{CO_2}} = 8.28$ USD/tCO_2 to calculate annual cost:

$$\text{Annual Tax (USD)} = x_{\mathrm{CO_2}} \times c_{\mathrm{CO_2}}$$

- **Policy Goal:** Incentivize operation at RPMs that minimize CO_2 per kWh. Operators are encouraged to maintain engines near optimum RPM for maximum EEI, reducing tax burden while maintaining power generation.

4.2 Automobile Sector: CO_2 Emission Modeling

4.2.1 Modeling Equations

For automobiles, emissions vary with engine load, distance traveled, and usage patterns. The monthly mileage-based model is:

$$
\begin{aligned}
KM_{it} &= \alpha + \beta_1 car1_{it} \cdot PKM1_{it} + \beta_2 car2_{it} \cdot PKM2_{it} \\
&\quad + \beta_3 car1_{it} \cdot y_{it} \cdot PKM1_{it} + \beta_4 car2_{it} \cdot y_{it} \cdot PKM2_{it} + \delta W_{it} + \xi X_{it} + a_i + \epsilon_{it}
\end{aligned}
\tag{4.3}
$$

where:

- KM_{it} : Monthly mileage of vehicle i in year t
- $car1$, $car2$: Indicators for first and second (or higher) cars
- PKM : Price per km depending on fuel type, age, and size
- y : Household income
- W : Usage vector (work, private, holiday, rural/urban roads)
- X : Vehicle characteristics
- a_i : Vehicle fixed effect
- ϵ_{it} : Error term

4.2.2 Taxation Policy for Automobile Sector

Using this model:

- **Assumptions:**
  - Public transport vehicles: 8 hours/day
  - Personal/private vehicles: 3 hours/day
- **Annual Emission Calculation:**
  - Multiply monthly mileage by vehicle-specific CO_2 emission factors to calculate annual CO_2 emissions.
  - Account for different fuels (Fuel P and Fuel Q) using emission per kWh or per km.
- **Carbon Tax:** Apply $c_{CO_2} = 8.28$ USD/tCO_2 to annual emissions:

$$\text{Annual Tax (USD)} = KM_{annual} \times EF \times c_{CO_2}$$

- **Sector-wise Policy:**
  - Public transport: Encourage operation at lower-emission speeds/RPMs to minimize total fleet tax.
  - Private vehicles: Tax based on individual annual mileage and CO_2 output to incentivize fuel-efficient driving and optimized vehicle usage.

4.2.3 Remarks

- The power plant sector allows precise RPM-based optimization, making taxation predictable and incentivizing efficient operation.

- Automobile emissions fluctuate with trip patterns and RPM; sector-specific taxation differentiates public vs private use, promoting efficiency and emission reduction.

- Annual carbon taxation aligns with environmental and economic objectives across the transport sector, ensuring both power generation and mobility sectors operate efficiently while minimizing CO_2 output.

Results and Discussion

5.1 Graphs

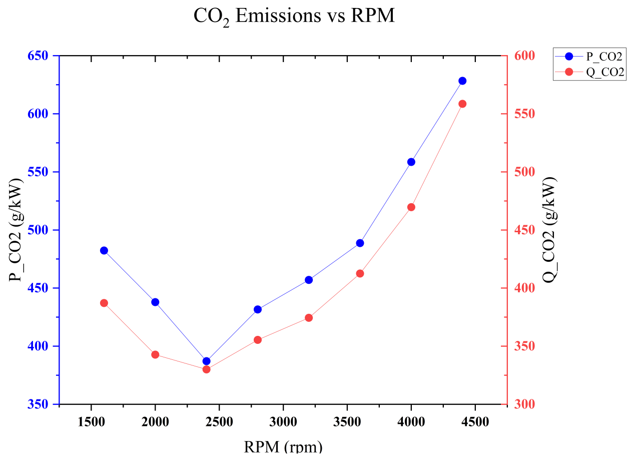


Figure 5.1: CO_2 Emission Vs RPM

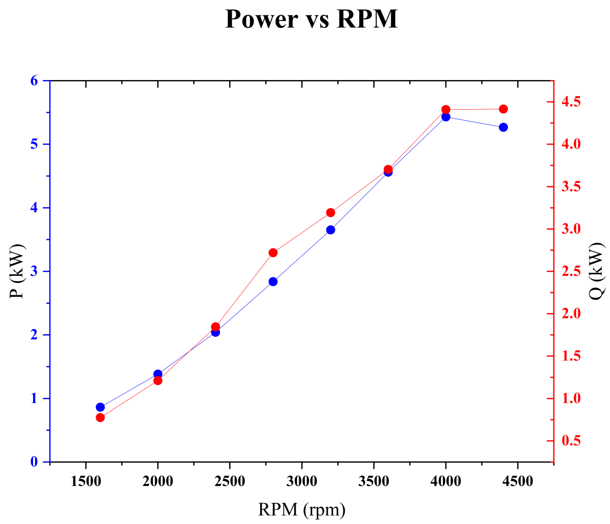


Figure 5.2: Power Vs RPM

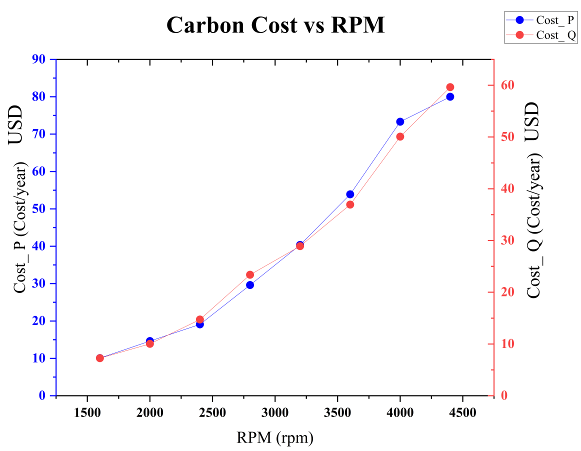


Figure 5.3: CO_2 pricing Vs RPM

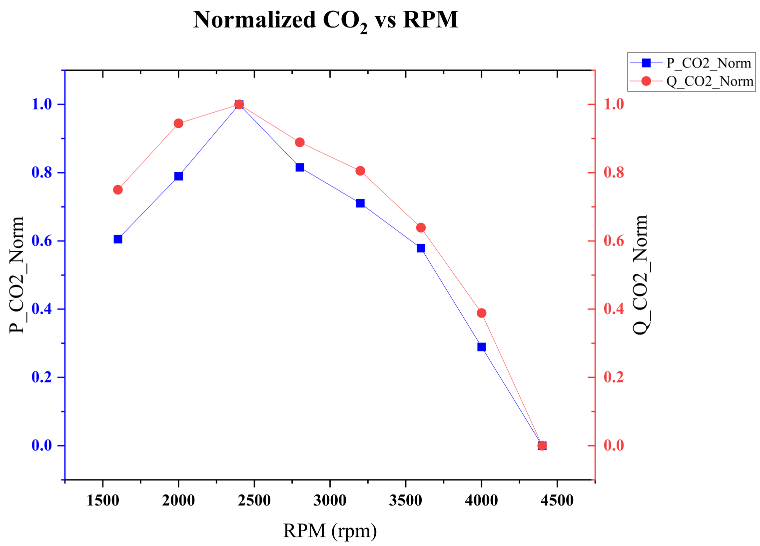


Figure 5.4: Normalized CO_2 Vs RPM

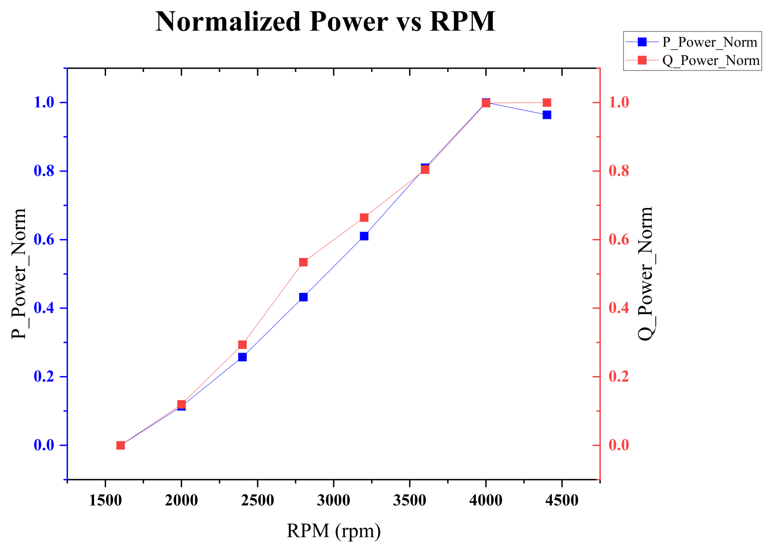


Figure 5.5: Normalized Power Vs RPM

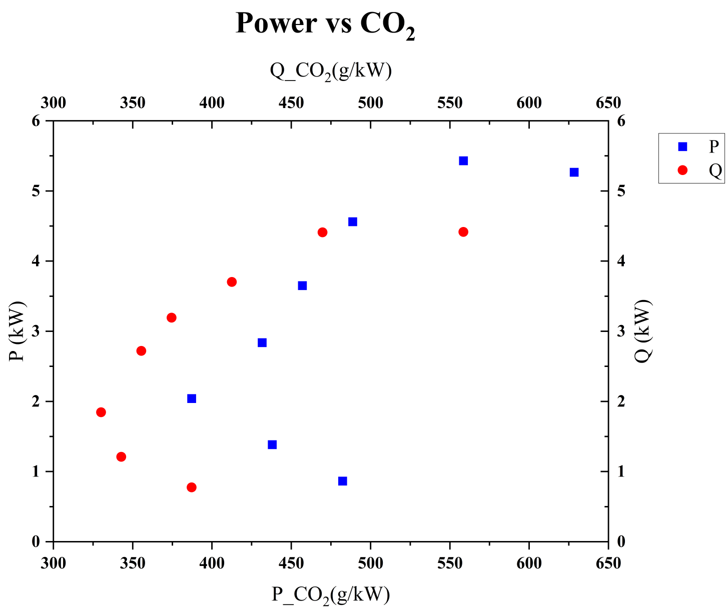


Figure 5.6: Power Vs CO_2 Emission

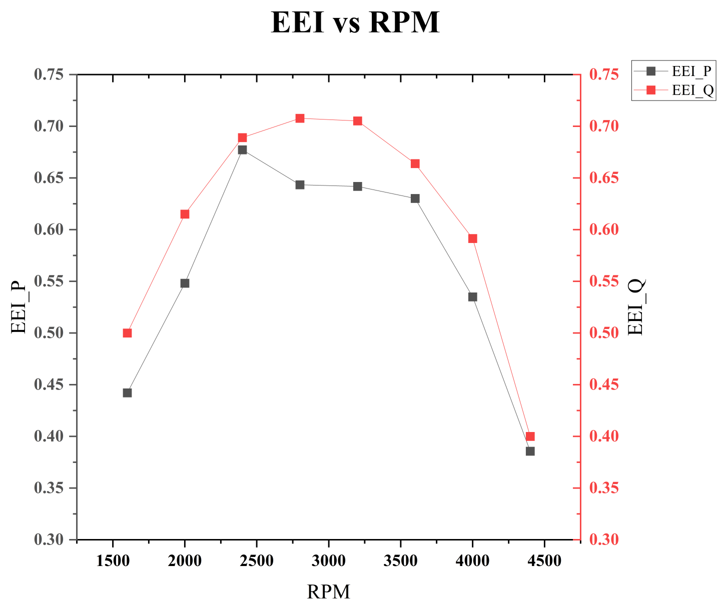


Figure 5.7: Enviro-Economic Index Vs RPM

The engine performance, CO_2 emissions, and associated economic costs were analyzed across the full range of operational RPMs for Fuels P and Q. Figures illustrate the relationships among power output, emissions, carbon cost, and the Enviro-Economic Index (EEI).

5.2 Engine Performance and CO_2 Emissions

The analysis indicates that both fuels exhibit increasing CO_2 emissions with RPM, as expected due to higher fuel consumption at elevated engine speeds. Fuel P consistently produces slightly lower emissions than Fuel Q at low to mid-range RPMs, while Fuel Q performs better in the high-RPM regime. Power output increases with RPM for both fuels; however, marginal gains in power at high RPMs are accompanied by disproportionate increases in CO_2 emissions and carbon costs (Figure 5.6), highlighting a critical trade-off between performance and environmental impact.

5.3 Enviro-Economic Index (EEI) Analysis

The EEI, integrating normalized power, CO_2 emissions, and carbon cost with weighted importance (0.4, 0.4, 0.2 respectively), shows an optimal operating range of 2400–2800 RPM. Fuel P achieves its maximum EEI at 2400 RPM (EEI = 0.677), whereas Fuel Q reaches the highest EEI at 2800 RPM (EEI = 0.708). This demonstrates that Fuel P is more efficient at lower RPMs, while Fuel Q becomes favorable at slightly higher engine speeds. At RPMs above 4000, EEI declines for both fuels, confirming the negative impact of excessive engine speed on enviro-economic performance.

5.4 Carbon Cost and Taxation Implications

Carbon costs calculated using a standardized price of 8.28 USD/tCO_2 reveal that Fuel Q incurs lower annual CO_2 costs at the optimized RPM, making it economically preferable despite slightly higher power consumption. The proposed taxation policy, applied to both the power plant and automobile sectors, effectively incentivizes operation near the RPM corresponding to maximum EEI, thus minimizing environmental and economic burden. Sector-specific approaches, distinguishing public versus private vehicles and power plant operations, ensure practical applicability of the carbon tax framework.

5.5 Observations

- Fuel P is preferable for low-to-mid RPM operation due to lower emissions and higher EEI at these speeds.
- Fuel Q becomes competitive at higher RPMs with lower CO_2 costs.
- Optimization confirms that high RPM operation marginally increases power but disproportionately increases emissions and cost.
- Integration of Caliskan method, normalization techniques, Minitab optimization, and Origin graphs provides a robust and data-driven framework for fuel selection and policy recommendation.

Overall, the results demonstrate the critical importance of integrating environmental, economic, and performance metrics for sustainable engine operation.

Conclusions

The enviro-economic and taxation analysis of Fuels P and Q provides the following key insights:

- **Optimal RPM Range:** Engine operation between 2400–2800 RPM achieves the best balance of power output, CO_2 emissions, and carbon cost for both fuels.
- **Fuel Performance:** Fuel P is advantageous at low-to-mid RPMs, while Fuel Q becomes more favorable at higher RPMs in terms of EEI and carbon cost.
- **EEI Effectiveness:** The Enviro-Economic Index successfully integrates power, emissions, and cost, guiding fuel selection and operational optimization.
- **Taxation Policy:** Carbon taxation based on modeled CO_2 emissions incentivizes optimal engine operation, differentiates between public and private vehicles, and aligns economic incentives with environmental objectives.
- **Trade-Off Analysis:** High RPM operation increases power slightly but incurs disproportionate CO_2 emissions and costs, confirming the need for strategic RPM management.
- **Modern Tool Integration:** The use of LaTeX for report formatting, Origin Pro for graphical visualization, Minitab for optimization, and the Caliskan method for annual emission and cost estimation provided a comprehensive, professional, and data-driven analysis framework.

The study demonstrates that integrating alternative fuel selection, engine optimization, and carbon-based taxation can significantly reduce environmental impact and promote sustainable energy use in Pakistan's transport and power sectors.