

Publications from the Research Work

Published Research papers

1. **Reetu Raj**, Deepak Kumar Singh, and J. V. Tirkey*. "Co-gasification of Low-grade coal with Madhuca longifolia (Mahua) biomass and dual-fuelled mode engine performance: Effect of biomass blend and engine operating condition." **Energy Conversion and Management** 269 (2022): 116150. (IF- 11.53).
2. **Reetu Raj**, Deepak Kumar Singh, and Jeewan Vachan Tirkey*. "Performance simulation and optimization of SI engine fueled with peach biomass-based producer gas and propane blend." **Thermal Science and Engineering Progress** 41 (2023): 101816. (IF- 4.8).
3. **Reetu Raj**, Jeewan Vachan Tirkey*, and Priyaranjan Jena. "Gasification of Briquette, Mahua wood, and Coconut shell and application to CI engines: Comparative performance and optimisation analysis." **Industrial Crops and Products** 199 (2023): 116758. (IF- 5.9).
4. **Raj Reetu**, Jeewan Vachan Tirkey, and Deepak Kumar Singh. "Parametric optimization and performance evaluation of gasifier-CI engine on dual fuel and dual feed material gasification." **International Journal of Ambient Energy** (2023): 1-28. (IF- 0.421).
5. **Raj Reetu**, and Jeewan Vachan Tirkey*. "Techno-economic assessment of sugarcane bagasse pith-based briquette production and performance analysis of briquette feed gasifier-engine system." **Journal of Environmental Management** 345 (2023): 118828. (IF- 8.7).
6. **Raj Reetu**, Singh, D.K. & Tirkey, J.V.*. Gasifier-engine performance analysis using Co-gasification of mahua wood waste and saw-dust briquette blend: an experimental and optimization approach. **Biomass Conversion and Biorefinery** (2023). (IF- 4.05).
7. **Reetu Raj**, Jeewan Vachan Tirkey*, Deepak Kumar Singh, Priyaranjan Jena, Co-gasification of waste triple feed-material blends using downdraft gasifier integrated with dual fuel diesel engine: An RSM-based comparative parametric optimization, **Journal of the Energy Institute**, Volume 109, 2023, 101271, ISSN 1743-9671. (IF- 5.7).
8. **Reetu Raj**, Deepak Kumar Singh, and Jeewan Vachan Tirkey. "Co-gasification of plastic waste blended with coal and biomass: a comprehensive review." **Environmental Technology Reviews** 12.1 (2023): 614-642.
9. Deepak Kumar Singh, **Reetu Raj**, and Jeewan Vachan Tirkey*."Performance and emission analysis of triple fuelled CI engine utilizing producer gas, biodiesel and diesel: An optimization study using response surface methodology." **Thermal Science and Engineering Progress** 36 (2022): 101486. (IF- 4.8).
10. Deepak Kumar Singh, **Reetu Raj**, Jeewan Vachan Tirkey*, Priyaranjan Jena, Prakash Parthasarathy, Gordon Mckay, Tareq Al-Ansari. Thermochemical conversion route for the production of hydrogen from agricultural Waste biomass and Plastic Waste: An Outlook & Critical review. **Environmental Technology Review**. (IF- 7.6).

11. Priyaranjan Jena, **Reetu Raj**, and Jeewan Vachan Tirkey*. "Thermodynamic performance study and RSM based optimization of SI engine using sewage sludge producer gas blend with methane." **Energy** 273 (2023): 127179. (IF- 9).
12. Priyaranjan Jena, **Reetu Raj**, Jeewan Vachan Tirkey*, Ajeet Kumar. "Experimental analysis and optimization of CI engine performance using waste plastic oil and diesel fuel blends." **Journal of the Energy Institute** 109 (2023): 101286. (IF- 5.7).
13. Priyaranjan Jena, Jeewan Vachan Tirkey*, **Reetu Raj**. 'Effect of Propane blending with Grape wood Producer gas on SI Engine performance and optimization.' **Applied Thermal Engineering**. (2024).

Revision Submitted Manuscripts

1. **Reetu Raj**, Jeewan Vachan Tirkey*, Priyaranjan Jena, Lawalesh Kumar Prajapati. 'Comparative analysis of Gasifier-CI Engine Performance and Emissions characteristics using diesel with producer gas derived from coal– briquette- coconut shell- mahua feedstock and its Blends.' **Energy**. (2024).
2. Jeewan Vachan Tirkey*, **Reetu Raj**, Priyaranjan Jena, Lawalesh Kumar Prajapati. 'Performance analysis of quasi-dimensional thermodynamic model of variable Hydrogen-methane fractions fuelled SI Engine: A simulation and RSM-optimization.' **International Journal of Ambient Energy**. (2024).
3. Priyaranjan Jena, Jeewan Vachan Tirkey*, **Reetu Raj**. 'Investigation on varied sewage sludge producer gas and methane blend equivalence ratios operated SI engine intact with Miller cycle strategy.' **International Journal of Ambient Energy**. (2024).

International Conferences

1. **Reetu Raj**, Valorization of gasified low-grade coal fly ash in concrete mixture and parametric optimization of engine performance and emission fuelled with producer gas. 4th International Conference on Opencast Mining Technology & Sustainability (ICOMS-2021, NCL Singrauli M.P (Poster presentation).
2. Deepak Kumar Singh, Jeewan Vachan Tirkey, **Reetu Raj**, Hemant Kumar, Ritesh Sonkar, Co-gasification of Low-grade coal and Waste Biomass blend: Experimental Investigation and RSM based parametric optimization of dual fuel CI Engine. 4th **International Conference on Opencast Mining Technology & Sustainability** (ICOMS-2021) on 13th -14th December 2021, at NCL Singrauli M.P.
3. **Reetu Raj**, Deepak Kumar Singh, and J. V. Tirkey*. 'Producer gas derived from Co-gasification of low-grade coal and waste mahua biomass: Engine application and optimization. **VII International Conference on "Sustainable Energy and Environmental Challenges"** (VII-SEEC) on 16th -18th December 2022, at IIT BHU.

- Priyaranjan Jena, **Reetu Raj**, Deepak Kumar Singh, Jeewan Vachan Tirkey*, Mathematical Simulation of SI engine performance using sewage sludge derived producer gas with methane blend, **VII International Conference on "Sustainable Energy and Environmental Challenges"** (VII-SEEC) on 16th -18th December 2022, at IIT BHU.

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- Chauhan, K. and V.P. Singh, *Prospect of biomass to bioenergy in India: An overview*. Materials Today: Proceedings, 2023.
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Reply to Examiners' Comments

I am very much grateful for the valuable feedback from the examiners that helped me to improve the quality of the PhD thesis. I have carefully responded to all points and have modified the thesis accordingly. Below is the responses of both the examiners-

Examiner-1

| S.No. | Comments | Amendment at the revised thesis |
|-------|---|--|
| 1 | Why not give a master chart early in the thesis (in the introduction chapter) outlining what has been done in chapters 2, 3, and 4. Please provide the experimental conditions, parameters, and range in this chart. | Section 1.6, Page no. 24 (Figure 1.3) |
| 2 | Why combining all the studies in one chapter (i.e., 4)? The size of each study deserves an individual chapter with its introduction and conclusions. This makes it easier to follow these studies and increase their visibility in the thesis. | <i>Chapter 4 Page no. 84, 116; Page no. 118, 139; Page no. 140, 172; Page no. 173, 202; Page no. 204, 237; Page no. 238, 272; Page no. 273, 299</i> |
| 3 | In the recommendation, why no suggestions have been made to consider AI/ML modelling as these methods are well developed nowadays and are being applied in many fields. | Section 5.3 (Page no. 315) last two bullet points |
| 4 | The economic studies/evaluations are based on the local Indian conditions. Although the author compared the results with some other studies showing the cost is US\$, would a limitation statement for the scope and conditions of this economic analysis and conclusions be appropriate? | Yes, the limitation statement for the scope and conditions of this economic analysis and conclusions is appropriate. <i>A conversion formula from INR to USD and converted amounts was given in Table 4.6.3. (Page no. 248). To validate the economic analysis results, sensitivity analysis (Net present value, and Profitability Index) was performed and the results are compared with other authors studies in USD (Page no. 248), and the results of current economic analysis are found to be compatible and economical viable with the literature.</i> |

Suggestions for Modification

| S.N | Page | Section | Comment | Amendment at the revised thesis |
|-----|-----------------|---|---|---|
| 1 | VII to XIV | Table of content | Check the format/style of headings. Usually, headings level 2 i.e., #.#, should have the first letter of each word capitalized. Currently, inconsistency exists. For example, compare headings 1.1, 1.2, and 1.3. This also applies to other levels of headings. For example, compare 3.3.1, 3.3.2, 3.3.3, and 3.3.4. Moreover, using bold format for a heading appears inconsistently, why 4.1 to 4.7 are in bold font, but 1.1, 2.1, 3.1 and all 2 level headings before 4.1 and also 5.1, 5.2, and 5.3 are not in bold font? Overall, please use systematic style | Page no.-VII-XIV Suggested format and style are incorporated |
| 2 | XVII, and XVIII | Fig. 4.4.4 and 4.4.6 | Fix the subscript of CO ₂ | Page no.-XVII, XVIII |
| 3 | XX | Fig. 4.6.16 | Why is the figure caption split on 3 lines? | Page no.- XX |
| 4 | XXVI | Abstract | The abstract is excessively long and is not finding-focused. There is no need for the current extended literature review description to identify the research gaps and justify what has been done in this thesis. I suggest that the first 2.5 pages of the abstract are shortened to one 10-lines paragraph to indicate the area, importance, and need for this research, then move directly to what this research did and give the major findings. I suggest that the part of the abstract (starting from the 2nd paragraph on page xxviii) is rewritten to focus more on the results/findings rather than describing how it was done, instead of saying we conducted RSM and ANOVA, we can say that RSM showed that and ANOVA revealed that the reader will know how you did the work. | Page no. - XXVI |
| 5 | XXVI | Abstract, line 10 | Replace "Worldwide, the availability of biomass is in abundant quantities" with "Worldwide, biomass is available in abundant quantities" | Page no.- XXVI, Line no.-6-7 |
| 6 | XXVI | | Change 'a potential source for biotransformation to fuels' to "biotransformed to fuels" | Page no.- XXVI, Line no.-9-10 |
| 7 | XXVIII | Abstract last line of 1 st paragraph | Replace "we have" with "the study has"? | Page no.- XXVII, Line no.-7 |

| | | | | |
|----|--------|---------------------------------------|---|---|
| 8 | XXVIII | 2 nd paragraph (1) and (2) | conduction" is a physical term with a specific meaning. I suggest using "conducting" to preserve the meaning. If this is accepted, then change "optimization" to "optimizing" Also, define "CI" and "PG" | Page no.- XXVII, Line no.-9-10; 13-14 |
| 9 | XXIV | 1 st paragraph | Define "SI" | Page no.- XXVIII, Line no.-5 |
| 10 | 1 | Line 2 | Delete 'As' | Page no.- 1; Line no.-2 (deleted) |
| 11 | 1 | Line 7-8 | (expected to be 10.9 billion at the end of the 21st century [3])" is a repetition of line 3 in the same section/paragraph. Please delete it | Page no.- 1; Line no.-7-8 (deleted) |
| 12 | 6-7 | Table 1.1 | When a table extends on multiple pages, it has to be divided in parts with the column headings are repeated in each part. | Page no.-6-7; Table 1.1 |
| 13 | 10 | Section 1.3.2 1 st line | When referring to a table or figure, use the same index, eg. "Table-1.1 is wrong; it must be "Table 1.1" | Page no.-9; Line no. 1 |
| 14 | 16 | 3 rd paragraph | Why the long indentation; it appears in several locations in the thesis, e.g., page 31, 78, 80, 114, 135, 169. Please check the entire thesis for this and fix it. | Page no.-16; 3 rd paragraph; entire thesis |
| 15 | 17 | Line 9 | Add space after "efficiency" before"" The same is in page 126 line 6 from the end of the page, page 136, | Page no.-17 (Line no. 9); Page no.-131 (Line no. 18) |
| 16 | 30 | Table 2.3.1 | When a table extends on multiple pages, please divide the table into parts and repeat the column's headings at each part. Keep the table number the same for all parts. This applies to several tables in the thesis, so please check them, E.g., pages 85-86 | Page no.-31 (Table 2.3.1); Page no.-90-91 |
| 17 | 38 | Line 7 in sec 2.5 | Define CR before using it. | Page no.- 40; Line no. 16 |
| 18 | 45 | The line before the last one | Define ICE | Page no.- 48 (2 nd last line) |
| 19 | 107 | | Add a space between the number and its units, e.g., 6.609ppm should be 6.609 ppm, there are several occasions like this on this page and other pages, e.g., page 117, line 10 in page 126, and 128, | Page no.- 109 (entire thesis) |
| 20 | 119 | Sec 4.2.1 line 3 | Why is the text font size of the dot at the end of the sentence so large and seems in bold? | Page no.- 124 (Line 3) |
| 21 | 122 | Line 6 | Add a comma “,” after “i.e.” | Page no.- 127 (Line 6) |
| 22 | 131 | | Response Surface Methodology appears in several instances in the thesis with different formats regarding capitalization. Please unify them. Why not give the | Page no.- XXVII, (Line no.-19) |

| | | | | |
|----|-----|---|---|---|
| | | | name the first time and use the abbreviation in the entire thesis? | |
| 23 | 135 | Line 7 from the bottom of the 1 st paragraph | Fix the subscript of CO ₂ | Page no.- 140 (Line 13) |
| 24 | 151 | Last line | "figure 4,3.6a" should be "Figure 4.3.6(a)" because this how it appears on page 153. Please check the entire thesis, and whenever you refer to a figure or a table that is in the thesis and has a number, it should start with a capital letter. See for example, page 183 line 3, page 184, and other locations in the thesis. Also see the word "table" in page 244. | Page no.- 156 (Last line); corrected throughout the entire thesis |
| 25 | 174 | Several locations | "NO _x " the "x" should be a subscript. | Page no.- 179 (entire thesis) |
| 26 | 294 | | "f- values" should be "F- values" | Page no.- 301 |
| 27 | 296 | 2 nd bullet | Add "is" before the "55.16%" | Page no.- 303 (2nd bullet) |

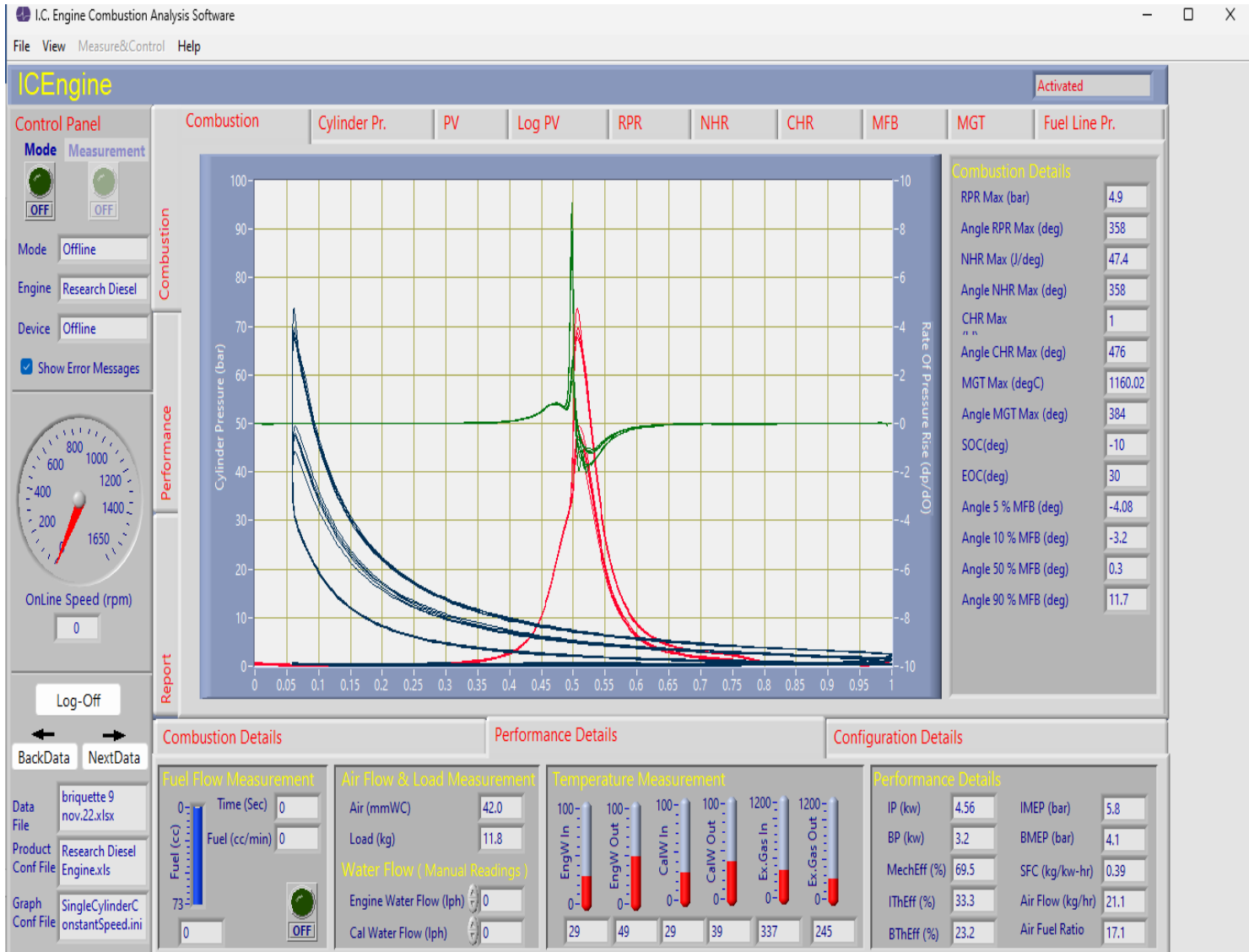
Examiner-2

| S.No. | Comments | Amendment at the revised thesis |
|-------|---|--|
| 1 | How does biomass gasification differ from other methods of biomass conversion? | <i>Section 1.2 (Page no. 5), Line no. 4-11</i> |
| 2 | How does biomass gasification work and what are the key parameters that affect the gasification process? | <i>Section 2.1 (Page no. 25-28), Section 2.2 (Page no. 28-30), and Section 2.4 (Page no. 37-38), and Page no. 5 (Line no. 14-22)</i> |
| 3 | What are the potential advantages and challenges of using biomass gasification for IC engine applications? | <i>Section 1.3.4 (Page no. 14-15)</i> |
| 4 | What are the different types of IC engines that can be used in conjunction with biomass gasification, and what are their respective advantages and disadvantages? | <i>Section 2.5, Page no 39-40</i> |
| 5 | What experimental methodologies were employed in this study to investigate the performance and emissions characteristics of biomass gasification for IC engine application? | <i>Section 3.1 Page no 48-54</i> |
| 6 | What were the main findings regarding the performance characteristics of biomass gasification in IC engine application, and how do they compare to other alternative fuel options? | <i>Page no. 126 (Figure 4.2.2), Page no. 127, Page no. 192 (Figure 4.4.8), Page no. 218 (Figure 4.5.6) Page no. 219-220 (Figure 4.5.7), Page no. 272, Page no. 307-308</i> |
| 7 | What were the emission characteristics observed when using biomass gasification In IC engine application, and how do they compare to conventional fossil fuel combustion? | <i>Page no. 129-134 (Figure 4.2.3, 4.2.4, 4.2.5, 4.2.6), Page no. 162 (Figure 4.3.8), Page no. 196 (Figure 4.4.10), Page no. 221-228 (Figure no. 4.5.8, 4.5.9, 4.5.10, 4.5.11), Page no. 272, Page no. 308</i> |
| 8 | How was the economic feasibility of biomass gasification for IC engine application assessed in this study, and what were the main factors considered? | <i>Section 3.2 (Page no. 59-65), Page no. (246-252)</i> |
| 9 | What were the main cost considerations associated with the implementation of biomass gasification for IC engine application, and what were the potential cost savings compared to conventional fuels? | <i>Page no. 62-65, 246, 250-252 (Table 4.6.4)</i> |
| 10 | What optimization strategies were explored in this study to enhance the overall performance and efficiency of biomass gasification for IC engine application? | <i>Page no. 77-81</i> |

| | | |
|----|---|----------------------------------|
| 11 | What were the key findings regarding the optimization of biomass gasification for IC engine application, and how do they contribute, to the advancement of technology? | Page no. 230-234 (Table 4.5.2) |
| 12 | What are the implications of the study's findings for the broader adoption and commercialization of biomass gasification for IC engine applications? | Page no. 313 (last paragraph) |
| 13 | What are the potential future research directions that can further enhance the understanding and application of biomass gasification for IC engine applications? | Section 5.3 Page no. 313-314 |
| 14 | How does the choice of biomass feedstock impact the gasification process and subsequent performance in IC engine applications? | Section 4.5.2 (Page no. 209-210) |
| 15 | What are the environmental implications and potential benefits of utilizing biomass gasification for IC engine applications, particularly in terms of greenhouse gas emissions and air pollution? | Page no. 311 |
| 16 | How does the scale of biomass gasification systems affect their economic viability and overall feasibility for widespread Implementation? | Page no. 251, 313 |
| 17 | What types of modifications or enhancements can be made to conventional IC engines to optimize their performance and compatibility with biomass gasification? | Page no. 49 (Last para.), 313 |
| 18 | What were the main challenges encountered during the experimental phase of this study, and how were they overcome or addressed? | Page no. 57 |

Appendix

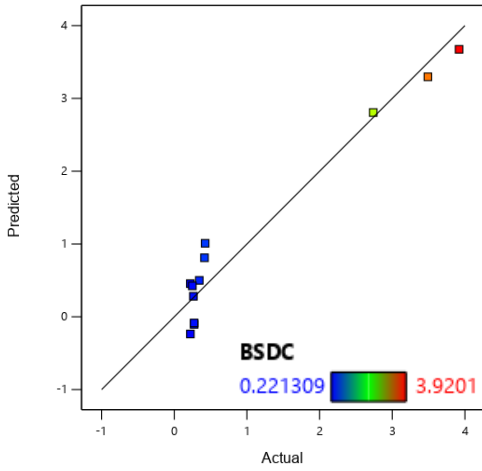
A0. Desktop view of IC Engine Combustion Analysis software



A1. Predicted vs Actual values of engine performance and emission analysis

Briquette

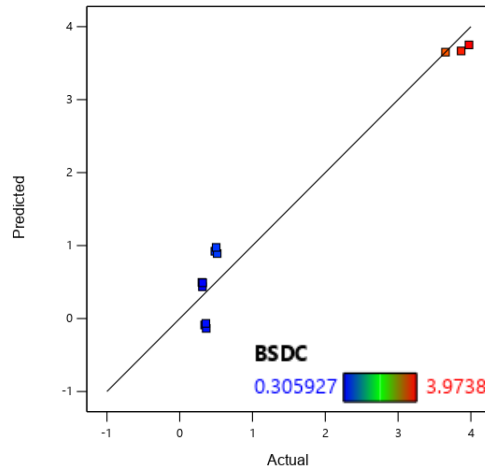
Predicted vs. Actual



1(a)

Mahua wood

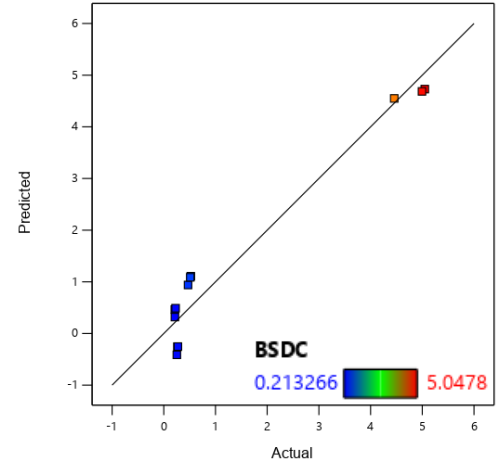
Predicted vs. Actual



1(b)

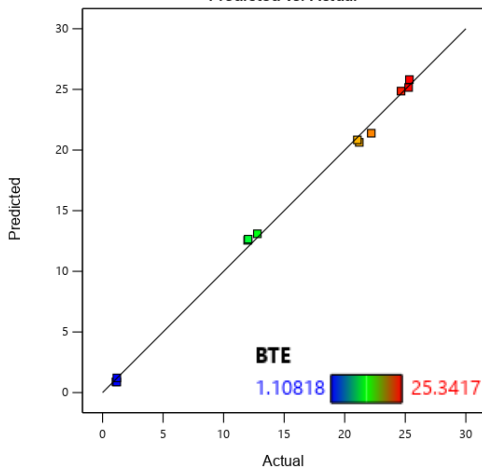
Coconut shell

Predicted vs. Actual



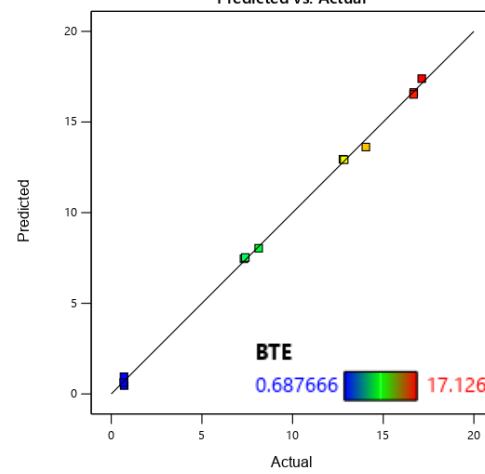
1(c)

Predicted vs. Actual



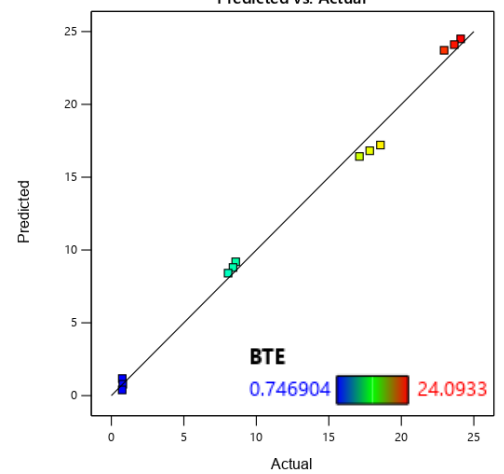
2(a)

Predicted vs. Actual

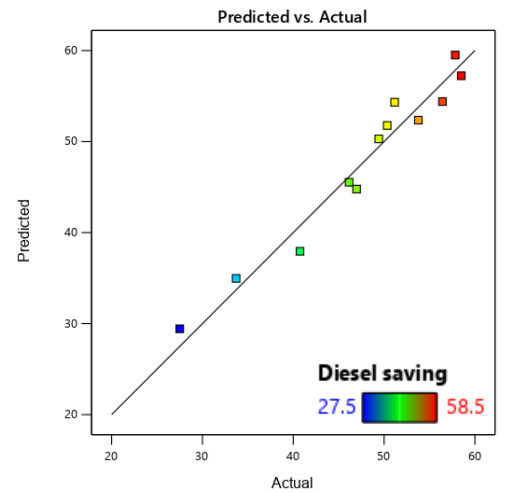
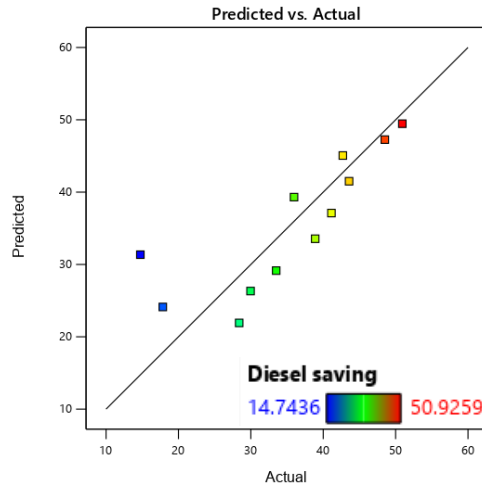
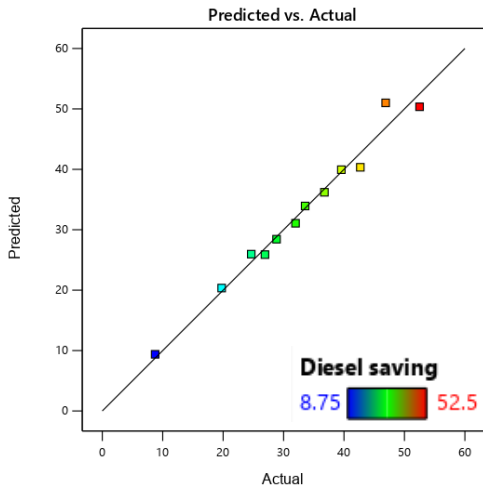


2(b)

Predicted vs. Actual



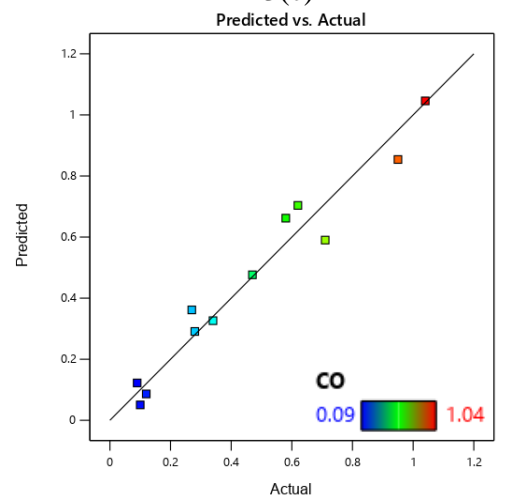
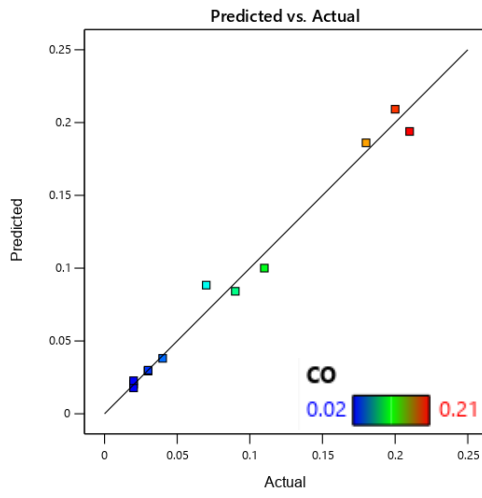
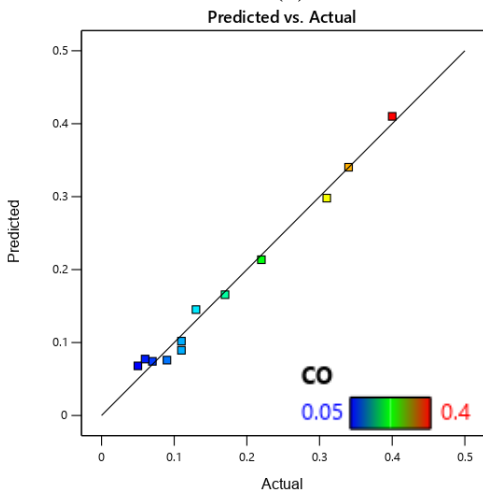
2(c)



3(a)

3(b)

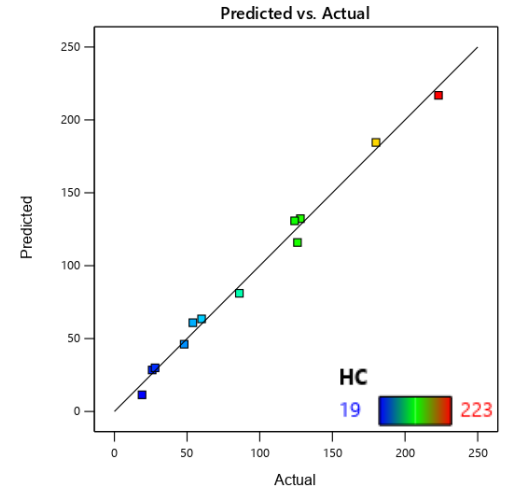
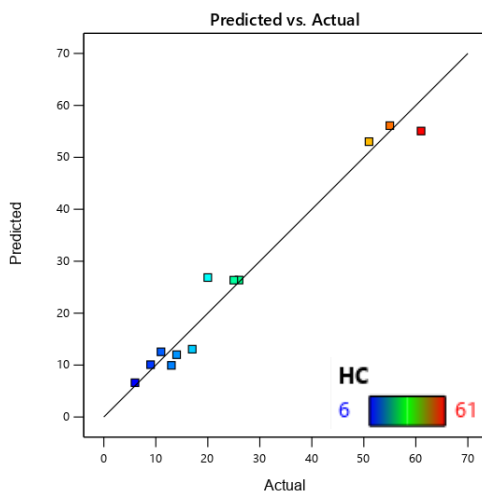
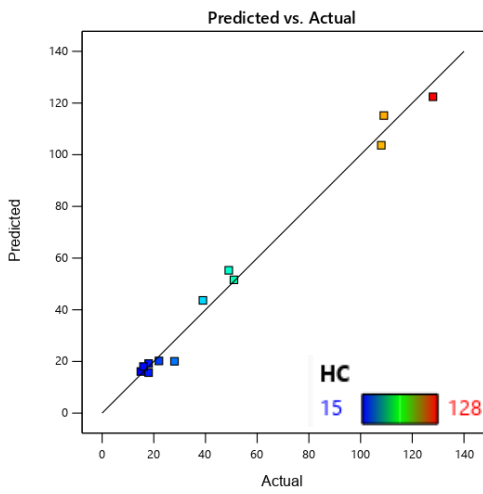
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4(a)

4(b)

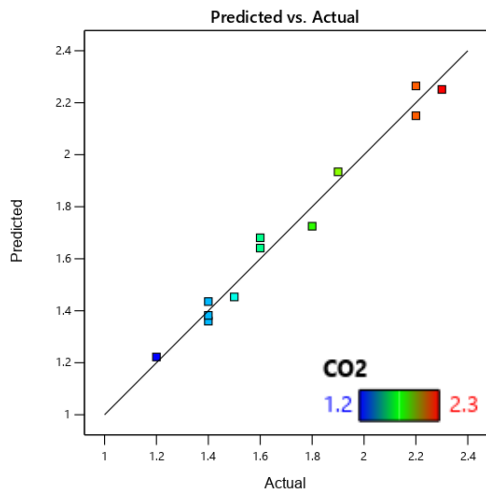
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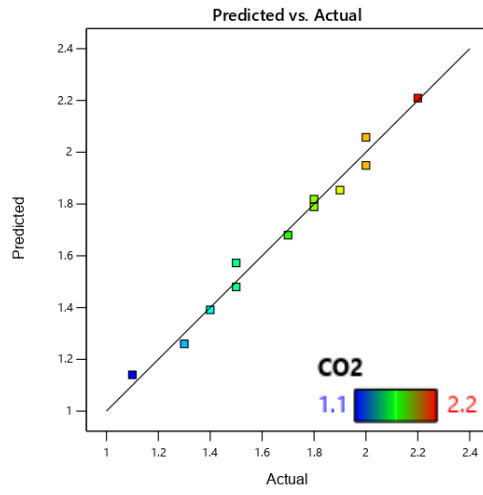
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5(b)

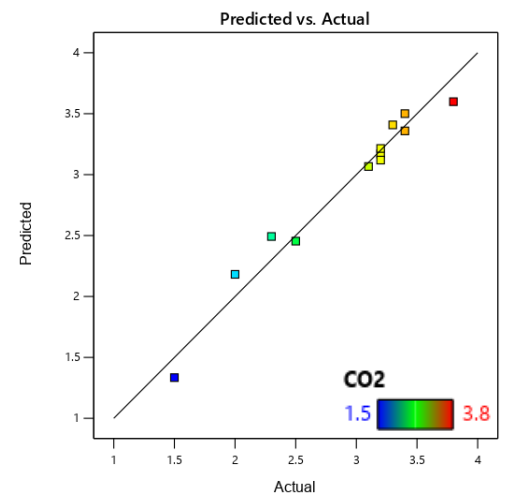
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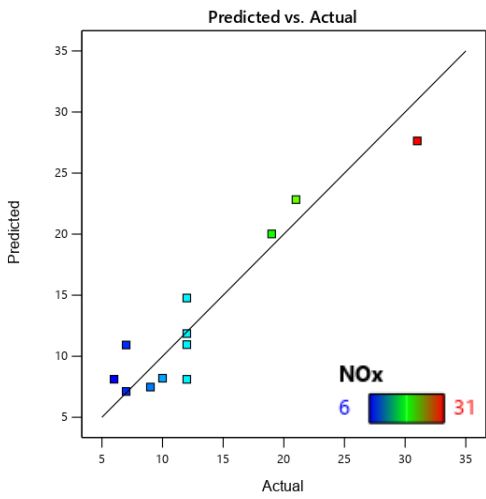
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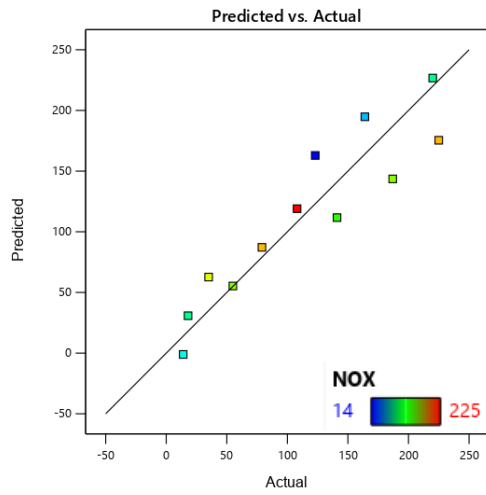
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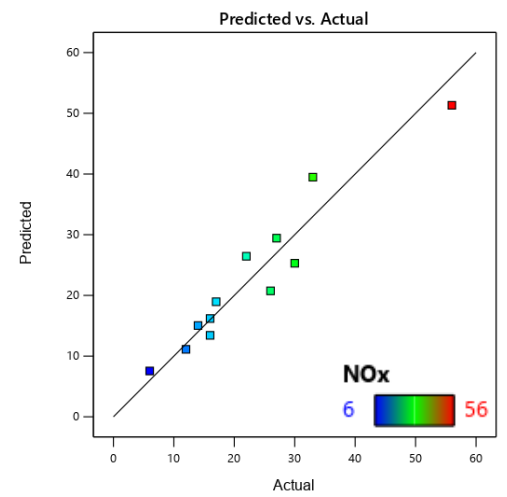
6(c)



7(a)



7(b)



7(c)

Figure 4.1.1S. Predicted vs. Actual values of the model for (1) BSDC; (2) BTE; (3) Diesel saving; (4) CO; (5) HC; (6) CO₂; and (7) NO_x using producer gas from (a) Briquette, (b) Mahua wood, and (c) Coconut shell on dual fuel mode.

A2. Perturbation Plots for engine performance and emissions

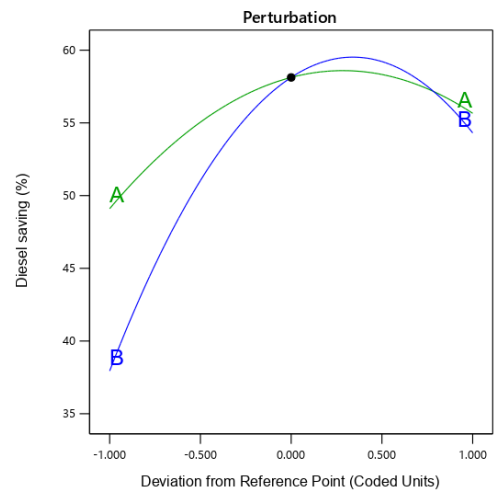
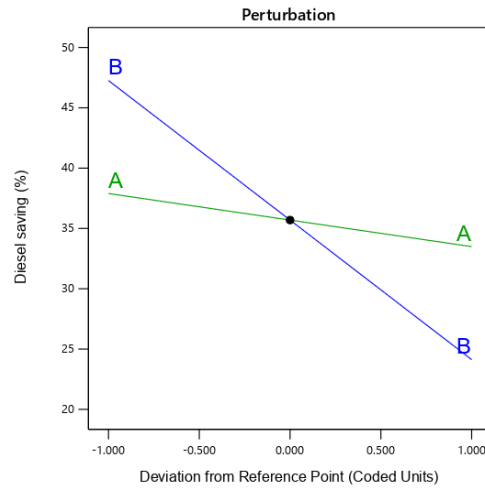
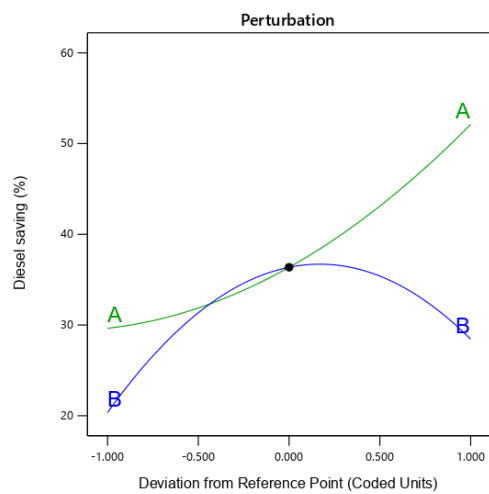
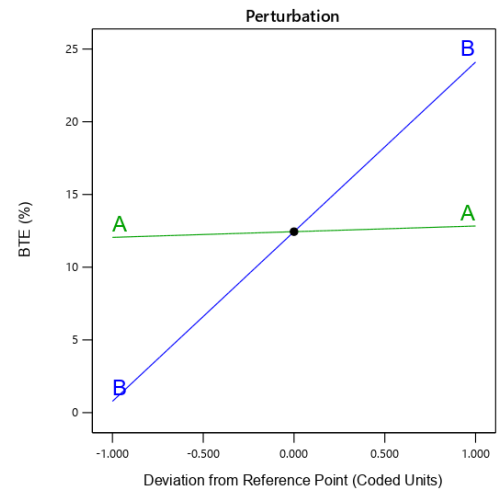
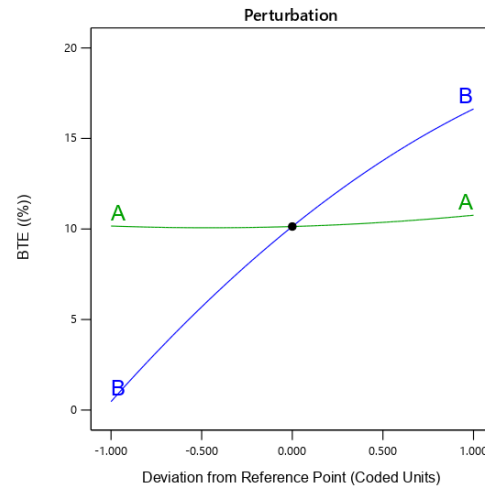
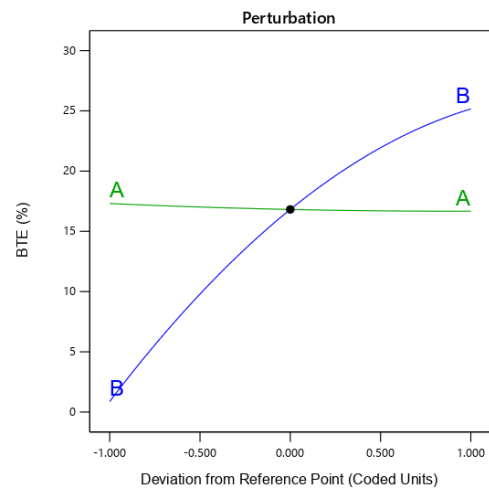
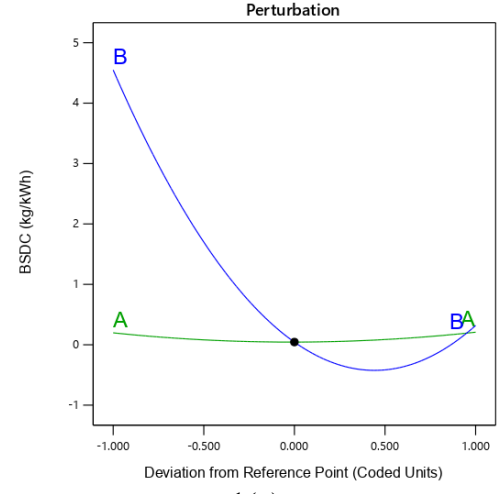
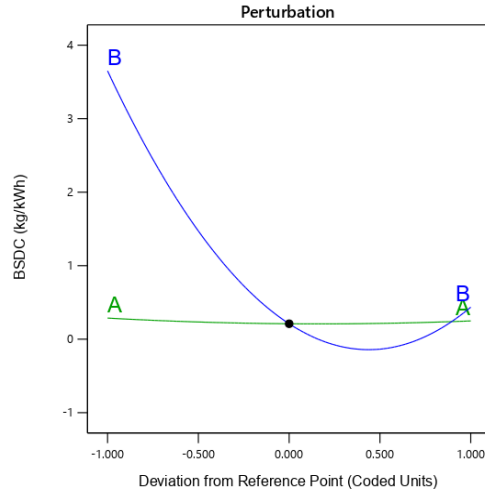
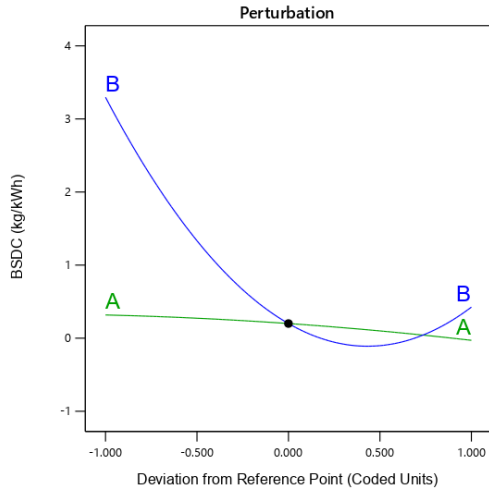
Briquette

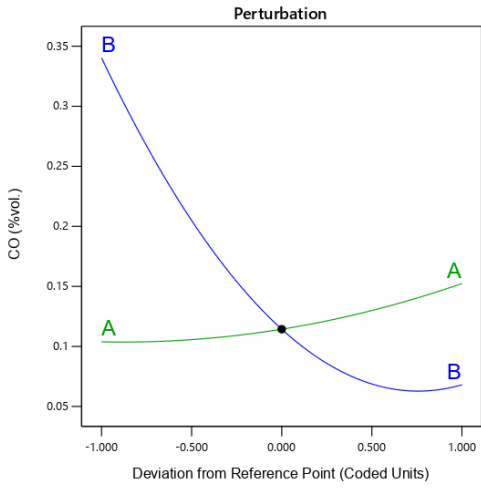
Mahua wood

Coconut shell

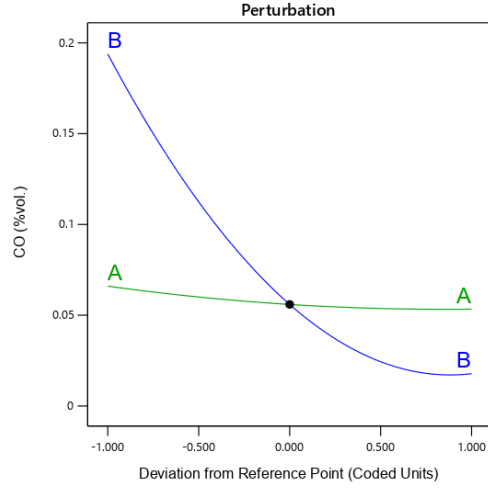
A: Compression ratio (CR);

B: Brake Power (BP)

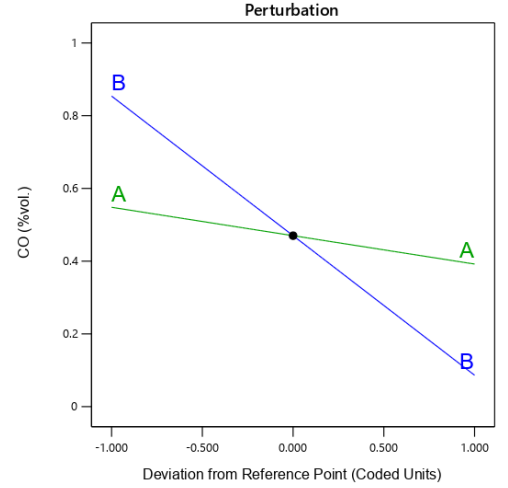




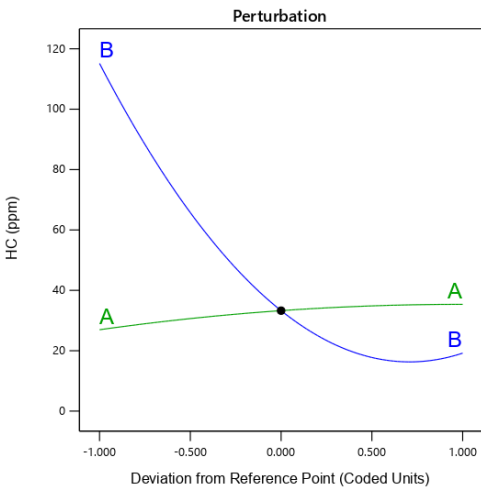
4(a)



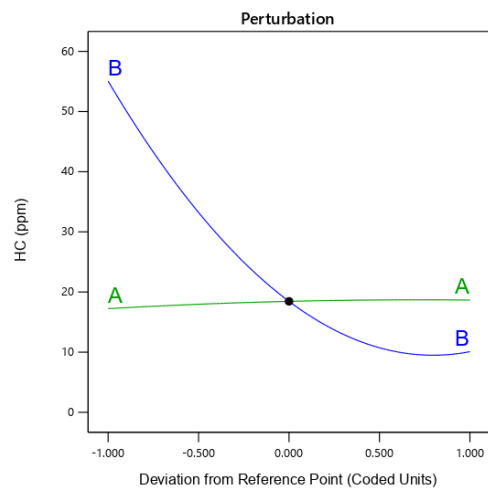
4(b)



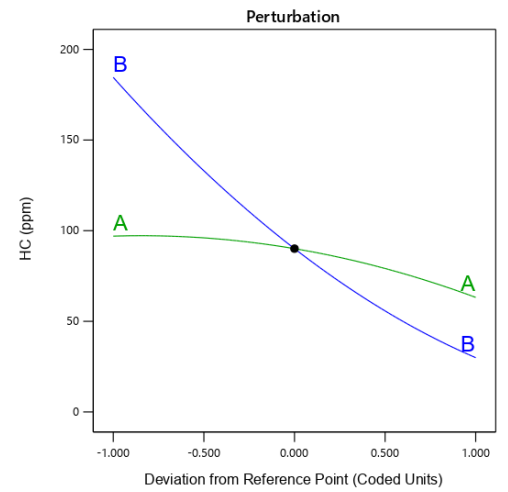
4(c)



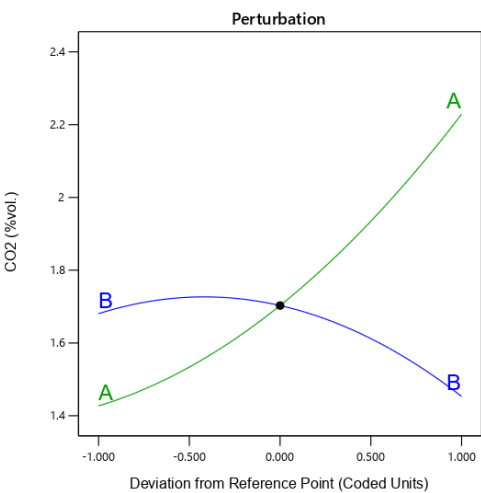
5(a)



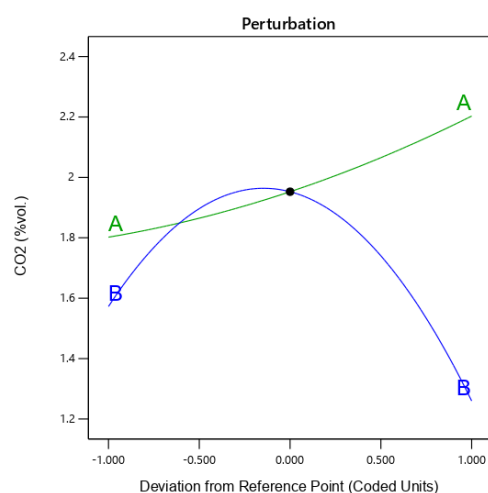
5(b)



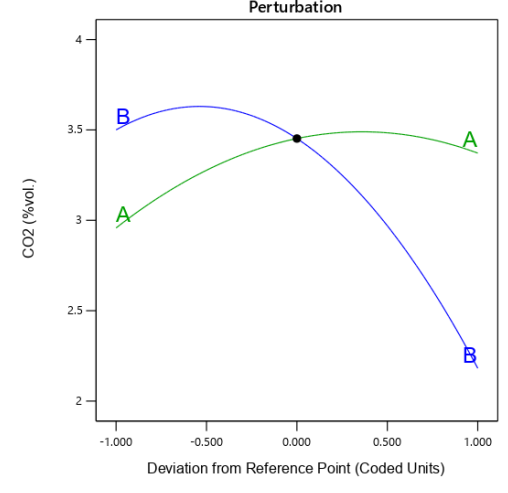
5(c)



6(a)



6(b)



6(c)

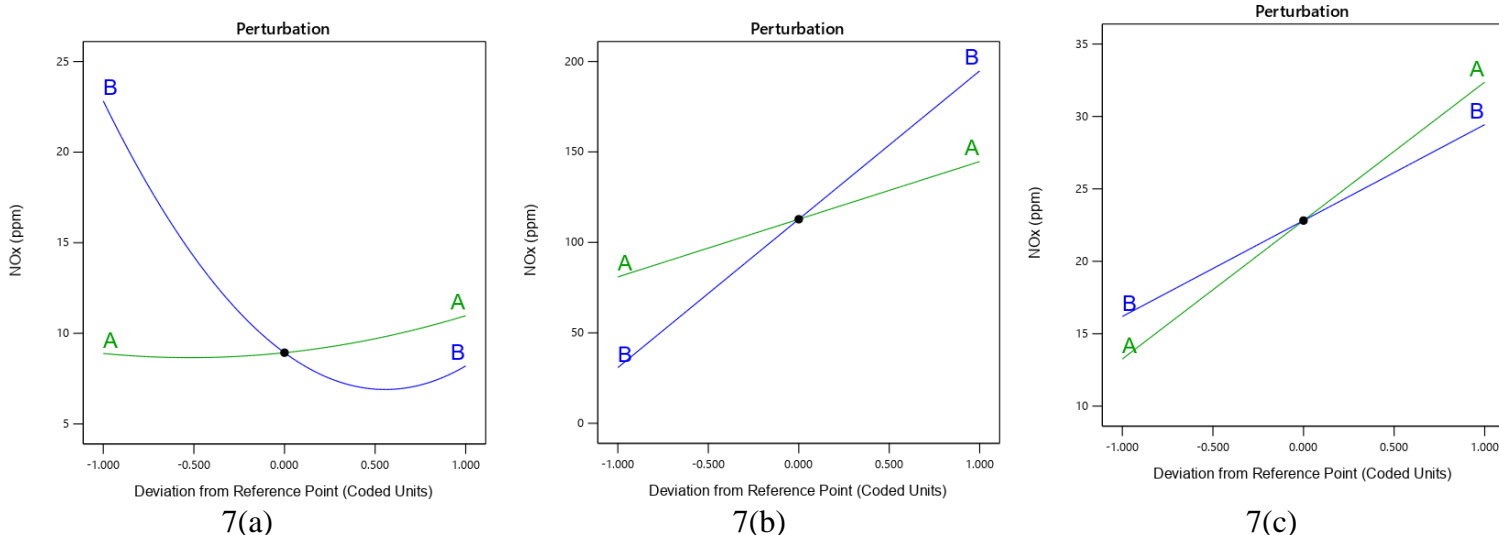


Figure 4.1.2S. Perturbation Plots for (1) BSDC; (2) BTE; (3) Diesel saving; (4) CO; (5) HC; (6) CO₂; and (7) NO_x using producer gas from (a) Briquette, (b) Mahua wood, and (c) Coconut shell on dual fuel mode.

Table 4.3.1S. ANOVA for engine's performance

| Source | DF | Sound | | BSFC | | BTE | |
|--------------------------|----|---------|---------|---------|---------|----------|---------|
| | | F-Value | P-Value | F-Value | P-Value | F-Value | P-Value |
| Model | 9 | 16.87 | 0.000 | 42.03 | 0.000 | 1201.88 | 0.000 |
| Linear | 3 | 44.63 | 0.000 | 82.78 | 0.000 | 3567.36 | 0.000 |
| ER | 1 | 0.07 | 0.788 | 1.40 | 0.244 | 18.36 | 0.000 |
| CR | 1 | 37.18 | 0.000 | 4.79 | 0.035 | 20.71 | 0.000 |
| BP | 1 | 96.63 | 0.000 | 242.1 | 0.000 | 10663.00 | 0.000 |
| | | | | 4 | | | |
| Square | 3 | 4.94 | 0.005 | 41.05 | 0.000 | 35.33 | 0.000 |
| ER*ER | 1 | 5.89 | 0.020 | 0.90 | 0.348 | 29.08 | 0.000 |
| CR*CR | 1 | 4.48 | 0.041 | 0.11 | 0.745 | 0.21 | 0.651 |
| BP*BP | 1 | 4.45 | 0.042 | 122.1 | 0.000 | 76.72 | 0.000 |
| | | | | 4 | | | |
| 2-Way Interaction | 3 | 0.98 | 0.411 | 2.86 | 0.049 | 6.79 | 0.001 |
| n | | | | | | | |
| ER*CR | 1 | 2.84 | 0.100 | 0.62 | 0.435 | 5.31 | 0.027 |
| ER*BP | 1 | 0.00 | 0.999 | 1.25 | 0.270 | 9.23 | 0.004 |
| CR*BP | 1 | 0.12 | 0.734 | 6.71 | 0.013 | 5.83 | 0.021 |
| Error | 38 | | | | | | |
| Total | 47 | | | | | | |
| R ² | | 94.3% | | 90.87% | | 99.65% | |

Table 4.3.2S. ANOVA for engine emissions

| Source | D F | CO | | HC | | CO ₂ | | NO _x | |
|-----------------|--------|-------------|-------------|-------------|-------------|-----------------|-------------|-----------------|-------------|
| | | F- Value | P- Value | F- Value | P- Value | F- Value | P- Value | F- Value | P- Value |
| Model | 9 | 66.21 | 0.000 | 53.77 | 0.000 | 54.54 | 0.000 | 4.31 | 0.001 |
| Linear | 3 | 165.34 | 0.000 | 127.81 | 0.000 | 108.14 | 0.000 | 6.05 | 0.002 |
| ER | 1 | 27.63 | 0.000 | 28.79 | 0.000 | 115.93 | 0.000 | 4.59 | 0.039 |
| CR | 1 | 0.07 | 0.792 | 3.66 | 0.063 | 50.03 | 0.000 | 3.87 | 0.056 |
| BP | 1 | 468.32 | 0.000 | 350.99 | 0.000 | 158.45 | 0.000 | 9.70 | 0.004 |
| Square | 3 | 26.10 | 0.000 | 24.71 | 0.000 | 50.33 | 0.000 | 1.76 | 0.171 |
| ER*ER | 1 | 72.12 | 0.000 | 54.26 | 0.000 | 128.74 | 0.000 | 0.68 | 0.415 |
| CR*CR | 1 | 0.01 | 0.928 | 0.33 | 0.571 | 0.00 | 1.000 | 0.00 | 0.954 |
| BP*BP | 1 | 6.16 | 0.018 | 19.54 | 0.000 | 22.26 | 0.000 | 4.60 | 0.038 |
| 2-Way | 3 | 7.11 | 0.001 | 8.73 | 0.000 | 4.81 | 0.006 | 5.29 | 0.004 |
| Interact | | | | | | | | | |
| ion | | | | | | | | | |
| ER*CR | 1 | 1.87 | 0.180 | 0.10 | 0.751 | 0.57 | 0.456 | 0.18 | 0.674 |
| ER*BP | 1 | 19.24 | 0.000 | 24.95 | 0.000 | 5.61 | 0.023 | 13.43 | 0.001 |
| CR*BP | 1 | 0.23 | 0.637 | 1.13 | 0.294 | 8.26 | 0.007 | 2.25 | 0.142 |
| Error | 38 | | | | | | | | |
| Total | 47 | | | | | | | | |
| R ² | | 94.01% | | 92.72% | | 92.8% | | 95.89% | |

A3. Response Optimizer: Setup

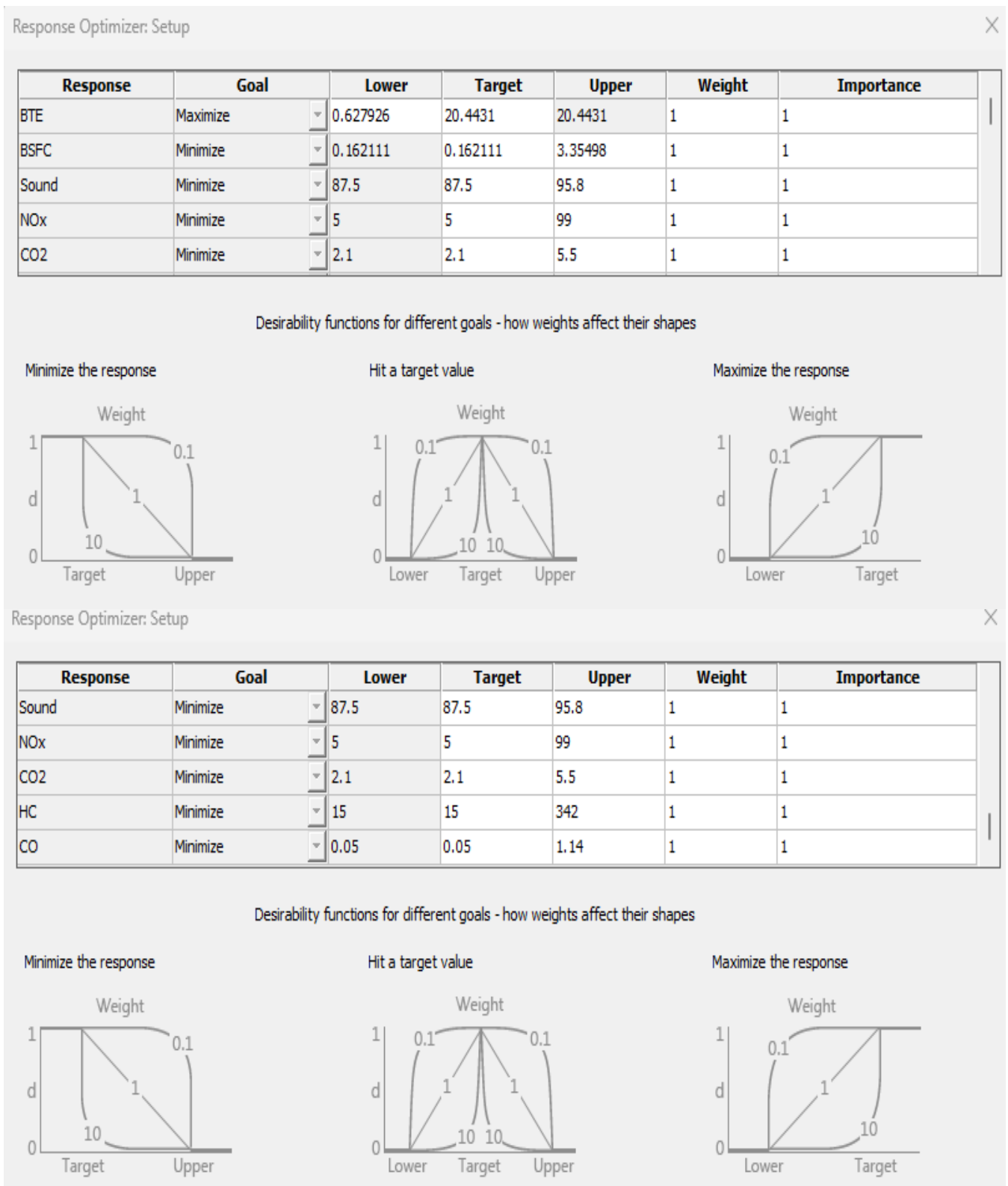


Figure 4.3.1S. Response optimiser setup

Table 4.6.1S. Analysis of Variance and Fit-Statistics of Engine performance

| Source | Sound | | | | | BTE | | | |
|--------------------|-------|---------|---------|---------|---------|---------|---------|---------|---------|
| | DF | Adj SS | Adj MS | F-Value | P-Value | Adj SS | Adj MS | F-Value | P-Value |
| Model | 9 | 406.763 | 45.196 | 104.62 | 0.000 | 5007.15 | 556.35 | 193.91 | 0.000 |
| Linear | 3 | 404.339 | 134.780 | 311.98 | 0.000 | 4294.79 | 1431.60 | 498.97 | 0.000 |
| GER | 1 | 6.080 | 6.080 | 14.07 | 0.001 | 66.47 | 66.47 | 23.17 | 0.000 |
| CR | 1 | 11.163 | 11.163 | 25.84 | 0.000 | 7.32 | 7.32 | 2.55 | 0.119 |
| Load | 1 | 387.096 | 387.096 | 896.02 | 0.000 | 4221.01 | 4221.01 | 1471.20 | 0.000 |
| Square | 3 | 1.472 | 0.491 | 1.14 | 0.347 | 697.30 | 232.43 | 81.01 | 0.000 |
| GER*GER | 1 | 0.653 | 0.653 | 1.51 | 0.226 | 10.55 | 10.55 | 3.68 | 0.063 |
| CR*CR | 1 | 0.788 | 0.788 | 1.83 | 0.185 | 11.00 | 11.00 | 3.83 | 0.058 |
| Load*Load | 1 | 0.030 | 0.030 | 0.07 | 0.794 | 675.75 | 675.75 | 235.53 | 0.000 |
| 2-Way | 3 | 0.953 | 0.318 | 0.74 | 0.538 | 15.06 | 5.02 | 1.75 | 0.173 |
| Interaction | | | | | | | | | |
| GER*CR | 1 | 0.333 | 0.333 | 0.77 | 0.385 | 7.10 | 7.10 | 2.47 | 0.124 |
| GER*Load | 1 | 0.168 | 0.168 | 0.39 | 0.537 | 7.66 | 7.66 | 2.67 | 0.110 |
| CR*Load | 1 | 0.452 | 0.452 | 1.05 | 0.313 | 0.30 | 0.30 | 0.10 | 0.749 |
| Error | 38 | 16.417 | 0.432 | | | 109.03 | 2.87 | | |
| Total | 47 | 423.180 | | | | 5116.17 | | | |
| R-sq | | | 96.12% | | | | | 97.87% | |
| R-sq (adj) | | | 95.20% | | | | | 97.36% | |
| R-sq (pred) | | | 93.70% | | | | | 96.48% | |

Table 4.6.2S. Analysis of Variance and Fit-Statistics of Engine emission

| Source | CO | | | | CO ₂ | | | | HC | | | | NO _x | | | | |
|--------------------|----|---------|---------|---------|-----------------|---------|---------|---------|---------|--------|--------|---------|-----------------|--------|---------|---------|---------|
| | DF | Adj SS | Adj MS | F-Value | P-Value | Adj SS | Adj MS | F-Value | P-Value | Adj SS | Adj MS | F-Value | P-Value | Adj SS | Adj MS | F-Value | P-Value |
| Model | 9 | 2.29543 | 0.25505 | 82.80 | 0.000 | 13.0174 | 1.44638 | 43.42 | 0.000 | 273733 | 30415 | 48.63 | 0.000 | 73113 | 8123.6 | 8.46 | 0.000 |
| Linear | 3 | 1.64159 | 0.54720 | 177.64 | 0.000 | 7.8270 | 2.60900 | 78.33 | 0.000 | 209936 | 69979 | 111.89 | 0.000 | 47875 | 15958.3 | 16.62 | 0.000 |
| GER | 1 | 0.05192 | 0.05192 | 16.86 | 0.000 | 1.3054 | 1.30537 | 39.19 | 0.000 | 14384 | 14384 | 23.00 | 0.000 | 37475 | 37475.0 | 39.02 | 0.000 |
| CR | 1 | 0.01665 | 0.01665 | 5.41 | 0.026 | 0.2812 | 0.28125 | 8.44 | 0.006 | 9180 | 9180 | 14.68 | 0.000 | 3983 | 3982.8 | 4.15 | 0.049 |
| Load | 1 | 1.57302 | 1.57302 | 510.65 | 0.000 | 6.2404 | 6.24037 | 187.35 | 0.000 | 186372 | 186372 | 298.00 | 0.000 | 6417 | 6417.0 | 6.68 | 0.014 |
| Square | 3 | 0.63226 | 0.21075 | 68.42 | 0.000 | 4.1292 | 1.37639 | 41.32 | 0.000 | 52753 | 17584 | 28.12 | 0.000 | 15449 | 5149.7 | 5.36 | 0.004 |
| GER*GER | 1 | 0.10925 | 0.10925 | 35.47 | 0.000 | 1.6502 | 1.65021 | 49.54 | 0.000 | 7351 | 7351 | 11.75 | 0.001 | 9833 | 9832.7 | 10.24 | 0.003 |
| CR*CR | 1 | 0.00008 | 0.00008 | 0.03 | 0.869 | 0.0937 | 0.09375 | 2.81 | 0.102 | 15 | 15 | 0.02 | 0.878 | 2871 | 2871.1 | 2.99 | 0.092 |
| Load*Load | 1 | 0.52292 | 0.52292 | 169.76 | 0.000 | 2.3852 | 2.38521 | 71.61 | 0.000 | 45387 | 45387 | 72.57 | 0.000 | 2745 | 2745.2 | 2.86 | 0.099 |
| 2-Way | 3 | 0.02158 | 0.00719 | 2.33 | 0.089 | 1.0613 | 0.35375 | 10.62 | 0.000 | 11044 | 3681 | 5.89 | 0.002 | 9789 | 3263.0 | 3.40 | 0.027 |
| Interaction | | | | | | | | | | | | | | | | | |
| GER*CR | 1 | 0.00028 | 0.00028 | 0.09 | 0.766 | 0.0562 | 0.05625 | 1.69 | 0.202 | 697 | 697 | 1.11 | 0.298 | 15 | 15.0 | 0.02 | 0.901 |
| GER*Load | 1 | 0.00216 | 0.00216 | 0.70 | 0.408 | 0.9690 | 0.96901 | 29.09 | 0.000 | 4824 | 4824 | 7.71 | 0.008 | 9673 | 9673.0 | 10.07 | 0.003 |
| CR*Load | 1 | 0.01914 | 0.01914 | 6.21 | 0.017 | 0.0360 | 0.03600 | 1.08 | 0.305 | 5523 | 5523 | 8.83 | 0.005 | 101 | 100.8 | 0.10 | 0.748 |
| Error | 38 | 0.11706 | 0.00308 | | | 1.2657 | 0.03331 | | | 23766 | 625 | | | 36497 | 960.4 | | |
| Total | 47 | 2.41248 | | | | | | | | 297499 | | | | 109609 | | | |
| R-sq | | | 95.15% | | | | 91.14% | | | | 92.01% | | | | 66.70% | | |
| R-sq (adj) | | | 94.00% | | | | 89.04% | | | | 90.12% | | | | 58.82% | | |
| R-sq (pred) | | | 91.85% | | | | 85.53% | | | | 86.85% | | | | 47.02% | | |

A4. Uncertainty calculations

The uncertainties in engine speed, load, intake charge volume and time measurements are presented as ΔN , Δm , ΔV and Δt in the following uncertainty calculations. ΔN is considered ± 10 RPM as per the manual specifications. Torque has been considered in terms of dynamometer load (mg) and arm length (l). The uncertainty was calculated considering blended dual fuel as it has greater CV. Further, ΔV and Δt is considered as ± 0.1 ml/min and ± 0.1 sec, respectively.

Example:

Percentage uncertainty in assessing engine speed: $\frac{\Delta N}{N} = \frac{10}{1500} = 0.667\%$

Percentage uncertainty in assessing engine load: $\frac{\Delta m}{m} = \frac{0.1}{12} = 0.833\%$

Percentage uncertainty for BP:

$$BP = \frac{2\pi NT}{60 \times 1000} = \frac{2\pi Nmg l}{60000} = \frac{2\pi \times 1500 \times 12 \times 9.81 \times 0.185}{60000} = 3.42 \text{ kW}$$

$$\frac{\partial BP}{\partial N} = \frac{2\pi mg l}{60000} = \frac{2\pi \times 12 \times 9.81 \times 0.185}{60000} = 0.00228061$$

$$\frac{\partial BP}{\partial m} = \frac{2\pi Ngl}{60000} = \frac{2\pi \times 1500 \times 9.81 \times 0.185}{60000} = 0.28507597$$

$$\begin{aligned} \Delta BP &= \sqrt{\left(\Delta N \times \frac{\partial BP}{\partial N}\right)^2 + \left(\Delta m \times \frac{\partial BP}{\partial m}\right)^2} \\ &= \sqrt{(10 \times 0.00228061)^2 + (0.1 \times 0.28507597)^2} = 0.03650755 \text{ kW} \end{aligned}$$

Thus, uncertainty = $\frac{\Delta BP}{BP} = \frac{0.03650755}{3.420912} = 1.067\%$

Percentage uncertainty for BSFC (at a fixed $v_f = 16.8$ ml/min):

$$FC = \frac{3600 \times v_f \times \rho}{t \times 1000} = \frac{3600 \times 16.8 \times 0.894}{60 \times 1000} = 0.901152 \frac{kg}{h}$$

$$\frac{\partial(FC)}{\partial t} = -\frac{3600 \times v_f \times \rho}{t^2 \times 10^6} = -\frac{3600 \times 16.8 \times 0.894}{60^2 \times 1000} = -0.0150192$$

$$\frac{\partial(FC)}{\partial v_f} = \frac{3600 \times \rho}{t \times 1000} = \frac{3600 \times 0.894}{60 \times 1000} = 0.05364$$

$$\begin{aligned} \Delta FC &= \sqrt{\left(\Delta t \frac{\partial FC}{\partial t}\right)^2 + \left(\Delta v_f \frac{\partial FC}{\partial v_f}\right)^2} = \sqrt{(0.1 \times (-0.0150192))^2 + (0.1 \times 0.05364)^2} \\ &= 0.0055703 \frac{kg}{h} \end{aligned}$$

$$BSFC = \frac{FC}{BP} = \frac{0.901152}{3.420912} = 0.2634245 \frac{kg}{kWh}$$

$$\frac{\partial(BSFC)}{\partial BP} = -\frac{FC}{BP^2} = -\frac{0.901152}{(3.420912)^2} = -0.0770042$$

$$\frac{\partial(BSFC)}{\partial FC} = \frac{1}{BP} = \frac{1}{3.420912} = 0.2923197$$

$$\begin{aligned} \Delta BSFC &= \sqrt{\left(\Delta BP \frac{\partial BSFC}{\partial BP}\right)^2 + \left(\Delta FC \frac{\partial BSFC}{\partial FC}\right)^2} \\ &= \sqrt{(0.03650755 \times (-0.0770042))^2 + (0.0055703 \times (0.2923197))^2} \\ &= 0.0032487 \frac{kg}{kWh} \end{aligned}$$

$$\text{Thus, } \frac{\Delta BSFC}{BSFC} = \frac{0.0032487}{0.2634245} = 1.233\%$$

Percentage uncertainty for BTE:

$$BTE = \frac{BP \times 3600 \times 100}{FC \times LHV} = \frac{3.420912 \times 3600 \times 100}{0.901152 \times 42000} = 32.5384\%$$

$$\frac{\partial(BTE)}{\partial BP} = \frac{3600 \times 100}{FC \times LHV} = \frac{3600 \times 100}{0.901152 \times 42000} = 9.511635$$

$$\frac{\partial(BTE)}{\partial FC} = -\frac{BP \times 3600 \times 100}{FC^2 \times LHV} = -\frac{3.420912 \times 3600 \times 100}{(0.901152)^2 \times 42000} = -36.107632$$

$$\begin{aligned} \Delta BTE &= \sqrt{\left(\Delta BP \frac{\partial BTE}{\partial BP}\right)^2 + \left(\Delta FC \frac{\partial BTE}{\partial FC}\right)^2} \\ &= \sqrt{(0.03650755 \times 9.511635)^2 + (0.0055703 \times (-36.107632))^2} \\ &= 0.4012898\% \end{aligned}$$

$$\text{Thus, } \frac{\Delta BTE}{BTE} = \frac{0.4012898}{32.5384} = 1.233\%$$

Percentage uncertainty in CO emission:

$$\sqrt{\left(\frac{\Delta CO}{CO}\right)^2 + \left(\frac{\Delta BP}{BP}\right)^2} = \sqrt{\left(\frac{0.03}{10}\right)^2 + (0.01067)^2} = 1.108\%$$

Percentage uncertainty in CO₂ emission:

$$\sqrt{\left(\frac{\Delta CO_2}{CO_2}\right)^2 + \left(\frac{\Delta BP}{BP}\right)^2} = \sqrt{\left(\frac{0.5}{20}\right)^2 + (0.01067)^2} = 2.718\%$$

Percentage uncertainty in NO_x emission:

$$\sqrt{\left(\frac{\Delta NO_x}{NO_x}\right)^2 + \left(\frac{\Delta BP}{BP}\right)^2} = \sqrt{\left(\frac{50}{5000}\right)^2 + (0.01067)^2} = 1.462\%$$

Percentage uncertainty in HC emission:

$$\sqrt{\left(\frac{\Delta HC}{HC}\right)^2 + \left(\frac{\Delta BP}{BP}\right)^2} = \sqrt{\left(\frac{10}{20000}\right)^2 + (0.01067)^2} = 1.06\%$$