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Optimization of Exhaust Emissions on FI Motorcycle using Programmable ECU and Ethanol Mixture with Taguchi Method

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Abstract. This study investigates fluctuations in carbon monoxide (CO) and hydrocarbon (HC) levels in exhaust emissions from fuel-injected (FI) motorcycles equipped with programmable ECUs. For each test, three different injection and ignition timings are used, as well as three distinct spark plug types and three ethanol combinations. The study's goal is to determine the best settings for reducing exhaust emissions. This experimental study used the Taguchi method with the L9 orthogonal array, with FI motorcycles serving as the major research object. The most significant impact on emissions was found by ANOVA analysis to be injector timing (factor D), which contributed 52.90% for carbon monoxide and 25.21% for hydrocarbons. The optimum approach to lower exhaust emission levels is to use an iridium spark plug, 350° ATDC injector timing, 5° BTDC ignition timing, and gasoline-ethanol (E30), according to the results of the experimental verification. The findings provide valuable insights for optimizing engine settings to meet stricter environmental regulations and enhance fuel efficiency, contributing to sustainable and eco-friendly transportation solutions.

1 Introduction

The current technological advancements include EFI (injection) and carburettor systems. Better combustion has been achieved by using EFI systems. The EFI of this motorcycle is electronically based, which means the signals from the sensors are transferred to the Electronic Control Unit (ECU) to manage the fuel delivery system electronically. It is expected that this EFI system will consume less fuel and produce higher power than the carburettor system [1].

Modifications to the engine, fuel system, air intake system, and ignition system during the combustion process are some of the methods used to lower pollution levels in cars. The

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systems in EFI (Electronic Fuel Injection) cars can be programmed as needed using a programmable ECU system, which is required to perform these tasks. The aftermarket offers reprogrammable ECUs, or programmable-type ECUs that allow for reprogramming of the vehicle's EFI (Electronic Fuel Injection) system [2,3].

The results of Firmansyah's research (2023) with the results of research on exhaust emissions experienced positive changes, which in the use of ECU programmable, ignition timing 7 o BTDC with injector timing 350 o ATDC and using E30 gasohol fuel obtained CO value of 0.02% CO2 level of 8.80% HC level of 480.3 ppm [3]. For ethanol mixtures, modifications to combustion components such as ignition timing, fuel injection, compression ratio, and octane number ratio are necessary to ensure optimal performance [4,5].

With EFI technology, users have the option to improve the performance of their motorbike, including torque, power, and fuel consumption. To improve the performance of EFI motorcycles, a standard ECU is changed to a programmable ECU. To perform this modification, the memory table of the ECU must be changed according to the needs [6,7].

Fuel is a substance that can be converted into energy. Petrol or gasoline is the most common fuel used in motorcycles because it is a hydrocarbon compound made from petroleum. Fuel oil that we know is not only the result of refining or refining petroleum, but also contains hydrocarbons. Furthermore, ethanol has a higher octane number than gasoline, as reported by some researchers [8–10]. Currently, there are several types of petrol fuel available in Indonesia. Premium fuel has an octane RON (Research Octane Number) of 88, Pertalite (RON 90), Pertamax (RON 92), and Pertamax Turbo (RON 98) [11].

Ethanol is a fuel that can be used in addition to petrol. Ethanol includes renewable energy from agricultural fermentation products such as corn, cassava, sugar cane, and others. Compared to fossil fuels, ethanol is cheaper to produce, has smaller hydrocarbon compounds that cause less pollution, and has an octane number of 111 that allows high ratios of up to 13:1. In addition, ethanol differs from petrol in that ethanol is an oxygenated fuel, where each compound contains 35% oxygen[4,12,13]. Life cycle assessment results in the literature show that corn-based ethanol can produce more CO2 (equivalent) per MJ of ethanol than sugarcane-based ethanol. Therefore, the fuel can be used in cleaner burning engines [13–15].

Mixturing ethanol with gasoline produces Gasohol (Gasoline-Ethanol). There are advantages to these blends as ethanol tends to increase octane number and reduce CO emissions. However, improper use of gasoline and ethanol blends can increase the amount of exhaust emissions [15,16]. The choice of a blend of ethanol and gasoline directly in a gasoline engine will have difficulty when burning, pure ethanol used in the engine will be difficult to start [14].

Gases released into the combustion chamber as a result of partially consumed fuel are known as exhaust emissions. Three essential elements are required for the combustion process: spark, proper fuel and air mixture, and combustion. If any of these fundamental requirements are not met, the combustion process cannot proceed. An ideal combustion process is required to create ideal exhaust gases, which consist of water vapour (H2O) and carbon dioxide (CO2)[17,18].

Hydrocarbons (HC) are unburned fuel produced by incomplete combustion, oil on the combustion chamber walls, and carbon. Due to its unburnable nature, higher hydrocarbon emissions will reduce engine power and increase fuel usage. Due to the high ratio of air and fuel when the engine is running, it produces carbon monoxide (CO). This is because oxygen cannot convert all the carbon from the fuel into carbon dioxide (CO2), so some part of the fuel does not burn and produces carbon monoxide (CO) [18–20].

2 Method

This research is classified as experimental research, which is a series of tests conducted on a series of variables whose values vary in response to certain treatments to examine the effects of changes in these variables [21]. According to Dr Genichi Taguchi, quality engineering has been used in Japan for several years. The purpose of quality engineering is to design a quality in each product and according to the process. The Taguchi method uses a special matrix in its use known as the Orthogonal Matrix or Orthogonal Array (OA). This method can be obtained from several data used with the number of experiments in order to get reproducible results with precision. Then this method can study the main effects so that it can be applied in screening / pilot experiments [22]. This study uses the taguchi method to make it easier to identify the optimal combination because the taguchi method is able to identify the optimal level of each factor to be studied using a small number of experiments but obtaining sufficient results [21,22]. We can be seen Specifications of gasoline and ethanol on **Table 1** and properties of gasoline-ethanol mixture on **Table 2**.

Table 1. Specifications of gasoline and ethanol

Properties	Gasoline	Ethanol
Research Octane Number (RON)	Various	106-115
Chemical Formulation	C_8H_{18}	C_5H_5OH
Purity (%)	n/a	99.5
Density (20 ºC) [kg/m^3]	3.88	2.06
Viscosity (20 ºC) [cSt]	0.64	1.52
Oxygen Content	0	34.73
Surface Tension (m/N/m)	21.58	22.66
Laten Heat of Vaporization [kJ/kg]	289	854
Stoichiometric (Air fuel ratio) [kg/kg]	14.7	

Table 2. Properties of gasoline-ethanol mixture

Properties	E0	E10	E20	E40	E60	E80
Flash Point (ºC)	-65	-40	-20	-13	-1	5
Autoignition Temperature (ºC)	246	260	279	294	345	362
Vapour Pressure (kPa at 37.8 ºC)	36	38.9	39	35.6	28	24
Energy Density (MJ/L)	34.2	33.2	32	30	28	26.5
Octane Number (RON)	92	93	94	97	100	104
Specific gravity	0.747	0.75	0.76	0.779	0.781	0.783

In this study, researchers used a FI motorccles as the object of research. Where previous research was conducted by Firmansyah (2023). In this study, the response variable used is exhaust emissions (Carbon Monoxide and Hydrocarbons) then the independent variables in this study are: Spark Plugs (Nickel, Iridium, Platinum), Injector Timing (360 o ATDC, 355 o ATDC, 350 o ATDC), Ignition Timing (5 o BTDC, 7 o BTDC, 9 o BTDC), Gasoline-Ethanol (E10, E20, E30). The research scheme and documentation can be seen in **Fig. 1** and 2 while the factor level codes can be seen in **Table 3**. In this study using four factors and each factor has three levels. Obtained from the number of factors and levels available so that the Orthogonal Matrix used is L9 (43) can be seen in **Table 4**.

Table 3. Factor Level Codes

Code of Factor	Factor	Code of Level		
		1	2	3
A	Spark Plug	Nickel	Iridium	Platinum
B	Injector Timing	360° ATDC	355° ATDC	350° ATDC
C	Ignition Timing	5° BTDC	7° BTDC	9° BTDC
D	Gasoline-Ethanol	E10	E20	E30

Fig. 1. (a) Schematic Diagram; (b) Research Documentation

Table 4. L9 Orthogonal array

Order	Factor							
	A	B	C	D	A	B	C	D
1	1	1	1	1	Nickel	360 ° ATDC	5 ° BTDC	E10
2	1	2	2	2	Nickel	355 ° ATDC	7 ° BTDC	E20
3	1	3	3	3	Nickel	350 ° ATDC	9 ° BTDC	E30
4	2	1	2	3	Iridium	360 ° ATDC	7 ° BTDC	E30
5	2	2	3	1	Iridium	355 ° ATDC	9 ° BTDC	E10
6	2	3	1	2	Iridium	350 ° ATDC	5 ° BTDC	E20
7	3	1	3	2	Platinum	360 ° ATDC	9 ° BTDC	E20
8	3	2	1	3	Platinum	355 ° ATDC	5 ° BTDC	E30
9	3	3	2	1	Platinum	350 ° ATDC	7 ° BTDC	E10

3 Result and Discussion

The following data on CO and HC levels at idle speed, the results can be seen in **Table 5**. Based on the data in **Table 5**, it can be derived into SNR response data which can be seen in **Table 6**. Based on **Table 6**, it can be seen that the optimal design of carbon monoxide is obtained at a combination of factor levels A2, B3, C1, D3, while for the optimal design of hydrocarbons is obtained at a combination of factor levels A2, B3, C1, D3. So, get the effect plot data of carbon monoxide and hydrocarbons in the following **Fig. 3** and **Fig. 4**.

The results of the data that have been obtained are then calculated to determine the analysis of variance. In **Table 7**, it can be seen that factor D significantly affects carbon monoxide and hydrocarbons.

Table 5. Exhaust emission test results of CO

Result of Carbon Monoxide and Hydro Carbon Emission Test														
Exp	**Factor**				**CO (%)**				**SNR**	**HC (ppm)**				**SNR**
	A	**B**	**C**	**D**	**R1**	**R2**	**R3**	**Ave**		**R1**	**R2**	**R3**	**Ave**	
1	1	1	1	1	7.81	6.75	3.85	6.14	16.07	765	563	305	544.33	55.21
2	1	2	2	2	3.98	4.02	2.54	3.51	11.08	362	303	283	316.00	50.04
3	1	3	3	3	3.98	2.68	1.57	2.74	9.29	284	255	208	249.00	47.99
4	2	1	2	3	1.98	2.44	0.52	1.65	5.29	251	291	255	265.67	48.51
5	2	2	3	1	4.35	5.17	4.79	4.77	13.59	299	298	328	308.33	49.79
6	2	3	1	2	1.43	0.91	1.74	1.36	2.94	218	155	221	198.00	46.03
7	3	1	3	2	4.59	4.34	4.24	4.39	12.85	357	302	326	328.33	50.35
8	3	2	1	3	0.26	0.25	1.02	0.51	4.09	215	152	167	178.00	45.11
9	3	3	2	1	5.07	3.78	4.09	4.31	12.77	388	251	292	310.33	49.98

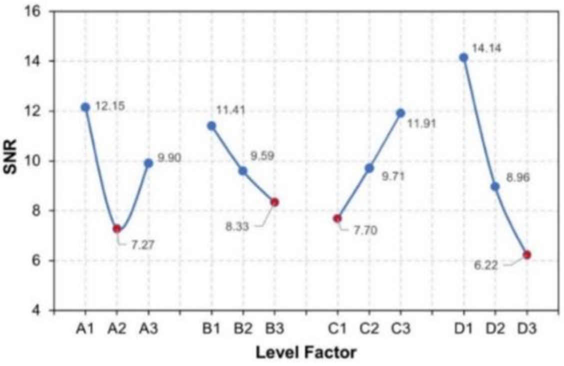

Fig. 3. Plot effect graph of CO

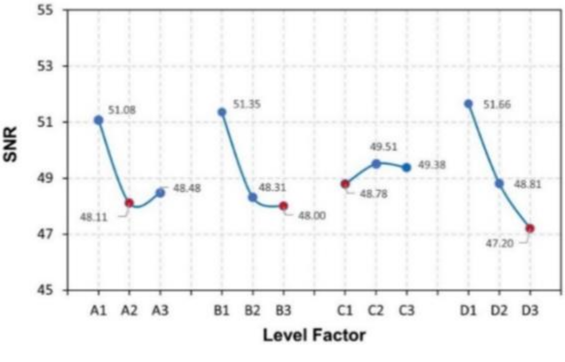

Fig. 4. Plot effect graph of HC

Table 6. SNR Response of CO and HC

Experiment	**Factor (%)**							
	CO (%)				**HC (ppm)**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Level 1	12.15	11.41	7.70	14.14	51.08	51.35	48.78	51.66
Level 2	7.27	9.59	9.71	8.96	48.11	48.31	49.51	48.81
Level 3	9.90	8.33	11.91	6.22	48.48	48.00	49.38	47.20
Max	12.15	11.41	11.91	14.14	51.08	51.35	49.51	51.66
Min	7.27	8.33	7.70	6.22	48.11	48.00	48.78	47.20
Diff	4.87	3.07	4.21	7.92	2.97	3.35	0.73	4.46
Rank	2	4	3	1	3	2	4	1
Optimal	A2	B3	C1	D3	A2	B3	C1	D3

Table 7. ANOVA of CO and HC

ANOVA												
Source	CO						HC					
	SS	DF	M	F ratio	SS'	Ratio (%)	SS	DF	M	F ratio	SS'	Ratio (%)
A	11.16	2	5.58	5.98	9.30	9.49	67147.56	2	33573.78	4.63	52642.74	13.14
B	8.56	2	4.28	4.59	6.69	6.83	86694.00	2	43347.00	5.98	72189.19	18.02
C	7.75	2	3.87	4.15	5.88	6.00	681.56	2	340.78	0.0	13823.26	3.45
D	53.67	2	26.84	28.76	51.81	52.90	115480.22	2	57740.11	7.96	100975.41	25.21
e	16.80	18	0.93	1	24.26	24.77	130543.33	18	7252.41	1	0.00	0.00
SSt	97.94	26	3.77		97.94	100	400546.67	26	15405.64		211984.07	53
Mean	287.79	1					2426401.33	1			52642.74	
SSTotal	385.73	27					2826948	27			72189.19	

The design is considered adequate if the experiments in the verification test and the prediction of the optimum conditions have close results. The optimal design of carbon monoxide and hydro carbon are A2, B3, C1, D3. The prediction results on the optimal design can be seen on **Table 8**, and results of carbon monoxide and hydrocarbon verification tests are shown in **Table 9**.

Table 8. Prediction test results of optimal design

Level Factor Optimal of CO					Level Factor Optimal of HC				
A2	B3	C1	D3	μ prediction	A2	B3	C1	D3	μ prediction
7.27	8.33	7.70	6.22	0.20	48.11	48.00	48.78	47.20	44.43

Table 9. Verification test results

Parameter	1	2	3	Average	μ prediction	S Dev.	SNR	SNR prediction	Error	Total Error
HC (ppm)	167	147	155	156.3	136.56	8.22	43.89	44.43	1.2%	95.1%
CO (%)	0.8	0.28	0.35	0.48	0.09	0.23	5.52	0.20	96.3%	

Based on **Fig. 3** and **Fig. 4** The results found that the test combination that obtained the optimal carbon monoxide and hydrocarbon value was by using iridium spark plug type, 350 oATDC injector timing, 5 o BTDC ignition timing, and E30 Gasoline-Ethanol (ethanol 30%: pertalite 70). The analysis of variance (ANOVA) from **Table 8** and **Table 9** highlighted the factors influencing emissions. For carbon monoxide, injector timing (factor D) was the most significant contributor, accounting for 52.90% of the variation, followed by spark plug type (factor A) at 9.49%, ignition timing (factor B) at 6.83%, and injector timing (factor C) at 6.00%. Similarly, for hydrocarbons, injector timing (factor D) was the dominant factor, contributing 25.21%, with ignition timing (factor B) at 18.02%, spark plug type (factor A) at 13.14%, and injector timing (factor C) at 3.45%. These findings underscore the critical role of injector timing in reducing emissions for both CO and HC.

Verification tests confirmed the validity of the results, demonstrating the reliability and adequacy of the research methodology. These findings align with previous studies highlighting the effectiveness of ethanol blends in reducing emissions due to ethanol's higher oxygen content, which improves combustion efficiency [22,23]. This study highlights the importance of optimizing ignition and injector timing in conjunction with the use of alternative fuels like E30 to effectively mitigate engine emissions. The findings can serve as a reference for future studies and provide practical guidance for developing cleaner, more efficient internal combustion engines.

4 Conclusion

The study determined that the optimal conditions for minimizing carbon monoxide and hydrocarbon emissions were using an iridium spark plug, 350° ATDC injector timing, 5°

BTDC ignition timing, and E30 Gasoline-Ethanol (30% ethanol, 70% pertalite). ANOVA analysis revealed that injector timing (factor D) had the most significant influence on emissions, contributing 52.90% for carbon monoxide and 25.21% for hydrocarbons. Verification tests confirmed the findings, proving the research was reliable and highlighting injector timing as the key factor in reducing emissions. The focus of this research is on the optimisation of the injection system and ignition system as well as the type of spark plug then using a mixture of bio gasoline fuel on CO and HC exhaust emissions on FI motorcycles. It is hoped that further research can conduct research on other performance.

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References

1. Sugiarto, T.; Putra, D.S.; Baharudin, A.; Kurniawan, D. Design and development of fuel consumption meter on motorcycle based on injector pulse width using arduino uno microcontroller. *BIS Energy Eng.* **2024**, *1*, V124032, doi:10.31603/biseeng.81.
2. Purwanto, W.; Maksum, H.; Arif, A.; Rochman, M.L.; Padrigalan, K.E. Exploration of Engine Parameters for Emission Reduction in Gasoline-Ethanol Fueled Engines. *Automot. Exp.* **2024**, *7*, 486–501.
3. Purwanto, W.; Firmansyah, M.S.; Maksum, H.; Arif, A. Analysis exhaust emissions (CO , CO 2 and HC) on FI motorcycle with variations in ignition timing , injector timing and fuel variations. In Proceedings of the Proceedings Series of Borobudur International Symposium on Energy and Engineering; 2024; Vol. 1, pp. 1–11.
4. Aakko-Saksa, P.; Koponen, P.; Roslund, P.; Laurikko, J.; Nylund, N.O.; Karjalainen, P.; Rönkkö, T.; Timonen, H. Comprehensive emission characterisation of exhaust from alternative fuelled cars. *Atmos. Environ.* **2020**, *236*, 117643, doi:10.1016/J.ATMOSENV.2020.117643.
5. Sulistyo, B.; Sofyan, H.; Sukardi, T.; Widyianto, A. Performance and Emission Characteristics Using Dual Injection System of Gasoline and Ethanol. *Automot. Exp.* **2023**, *6*, 245–258, doi:10.31603/AE.8070.
6. Sharma, N.; Agarwal, A.K. Effect of fuel injection pressure and engine speed on performance, emissions, combustion, and particulate investigations of gasohols fuelled gasoline direct injection engine. *J. Energy Resour. Technol. Trans. ASME* **2019**, *142*, doi:10.1115/1.4044763.
7. Meetam, K.; Gonsrang, S.; Dechwayukul, C.; Kaewapichai, W.; Neranon, P.; Vittayaphadung, N.; Auysakul, J. Modeling and Tuning of Electronic Throttle Control System in Formula Student Car. *Int. J. Automot. Mech. Eng.* **2023**, *20*, 10917–10930, doi:10.15282/ijame.20.4.2023.09.0844.
8. Hanifuddin, M.; Taufiqurrahman, M.F.; Setyawan, T.A.; Anggarani, R.; Wibowo, C.S.; Sugiarto, B. Performance of a Single-Cylinder Four-Stroke Engine with High Concentrations of Gasoline-Ethanol-Methanol (GEM). *Automot. Exp.* **2023**, *6*, 407–415, doi:10.31603/ae.9332.
9. Rashid, A.K.; Mansor, M.R.A.; Ghopa, W.A.W.; Harun, Z.; Wan, W.M.F.M. An experimental study of the performance and emissions of spark ignition gasoline engine. *Int. J. Automot. Mech. Eng.* **2022**, *13*, 3540–3554, doi:10.15282/ijame.13.3.2016.1.0291.
10. Susanto, M.T.; Andrizal; Martias Pengaruh Jenis Bahan Bakar Bensin terhadap Daya, Torsi, dan Emisi pada Sepeda Motor 4 Tak. *J. Mech. Electr. Ind. Eng.* **2019**, *1*, 1–6.
11. Wibowo, C.; Adian, F.; Nugroho, Y.; Sugiarto, B. The optimization of the relationship

between octane number of gasoline-ethanol blend fuels in various settings of the engine control module. *Evergreen* **2020**, *7*, 587–592, doi:10.5109/4150510.
12. Purwanto, W.; Tsong Su, J..; L.R., M.; Waluyo, B.; Krsmadinata; Arif, A. Study on the Addition of A Swirling Vane to Spark Ignition Engines Fueled by Gasoline and Gasoline-Ethanol. *Automot. Exp.* **2023**, *6*, 162–172.
13. Wahyu, M.; Rahmad, H.; Gotama, G.J. Effect of cassava biogasoline on fuel consumption and co exhaust emissions. *Automot. Exp.* **2019**, *2*, 97–103, doi:10.31603/ae.v2i3.3004.
14. Syarifudin; Sanjaya, F.L.; Fatkhurrozak, F.; Usman, M.K.; Sibagariang, Y.; Koten, H. Effect methanol, ethanol, Butanol on the emissions characteristics of gasoline engine. *Automot. Exp.* **2021**, *4*, 62–67, doi:10.31603/ae.4641.
15. Mendiburu, A.Z.; Lauermann, C.H.; Hayashi, T.C.; Mariños, D.J.; Rodrigues da Costa, R.B.; Coronado, C.J.R.; Roberts, J.J.; de Carvalho, J.A. Ethanol as a renewable biofuel: Combustion characteristics and application in engines. *Energy* **2022**, *257*, 124688, doi:10.1016/J.ENERGY.2022.124688.
16. Warju, K.; Sudirman, R.S.; Muhammad, Y.P.; R.F. Optimization of Metallic Catalytic Converters to Reduce CO Emissions and Increase Engine Power. *Automot. Exp.* **2024**, *7*, 299–309.
17. B. Amin; F. Ismet *Teknologi Motor Bensin*; Kencana: Jakarta, 2016;
18. Tian, H.; Wang, J.; Zhang, R.; Zhang, Y.; Su, Y.; Yu, H.; Shen, B. Experimental Study on Macroscopic Spray and Fuel Film Characteristics of E40 in a Constant Volume Chamber. *Energies* **2023**, *16*, doi:10.3390/en16227488.
19. Amin, B.; Ismet, F. *Teknologi Motor Bensin*; Kencana: Jakarta, 2016;
20. Mokhtar, M.; Sugiarto, B.; A. A., A.; Kurniawan, A.; S. A., A.; A. N., B. Investigating Knocking Potential, Cycle Stability, and Emission Characteristics in Lean Spark Ignition Engine with Gasoline, Ethanol, and Methanol. *Automot. Exp.* **2024**, *7*, 48–62.
21. Setyanto, N.W.; Lukodono, R.P. *Teori dan Aplikasi Desain Eksperimen Taguchi dalam Melakukan Penelitian*; UB: Press: Malang, 2017;
22. Ganesan, N.; Ishan Sahni; Samuel, O.D.; Enweremadu, C.C.; Veza, I.; Chandran, D. Optimization and sustainability of gasohol/hydrogen blends for operative spark ignition engine utilization and green environment. *Case Stud. Therm. Eng.* **2022**, *39*, doi:10.1016/j.csite.2022.102381.
23. Alemayehu, G.; Firew, D.; Nallamothu, R.B.; Wako, A.; Gopal, R. Operating parameters optimization for lower emissions in diesel engine with PCCI-DI mode using Taguchi and grey relational analysis. *Heliyon* **2022**, *8*, e09679, doi:10.1016/j.heliyon.2022.e09679.