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FUZZY LOGIC IMPROVED CONTROL DESIGN FOR ELECTRO-PNEUMATIC CLUTCH ACTUATION SYSTEM IN HEAVY DUTY VEHICLES

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Abstract

This presentation focuses on enhancing the performance index of clutch actuation control process in an electro-pneumatic clutch system for heavy duty vehicles. The current weaknesses in performances of heavy-duty vehicles especially on hilly terrains which often lead to accidents can be traced to inadequacies in clutch actuation control. At present, conventional control techniques in clutch actuation uses on/off, servo mechanism and other non-intelligent methods of actuation control which calls for frequent but often neglected calibration of clutch actuators. To eliminate calibration and its observed defects, an intelligent method of clutch actuation modeled in a fuzzy logic control is adopted. Conventional data obtained for errors, speed, torque and power from Mercedes Benz Actros Truck model MP 2 served as reference points. An intelligent agent-based actuation rule, modeled in a fuzzy logic fashion was developed. The Mandani model of fuzzy inference system in a MATLAB environment was adopted for the design. The fuzzy logic control of forty-nine rules was developed for the input and three levels of outputs were obtained. Simulink models for both conventional and fuzzy logic controllers were also developed and simulated. Different percentages of improvements were recorded for piston error, engine torque, angular speed and power respectively in order to justify the research. An average percentage of improvements on conventional controllers compared to the fuzzy controllers stood at an error reduction in clutch travel from 0.720mm to 0.04171mm given an average reduction of 0.3029mm or a percentage decrease of 42%. For the engine torque, an average increase from 0.18 NM to 0.21 NM or an increase of 0.03 NM, given a percentage increase of 15% was recorded. Similarly, increases were observed for power and angular speed. Power increased from an average of 16.88 kilowatts to 18.25 kilowatts, resulting in 1.37kilowatts increase or 8 %, while angular speed was also increased from 1005 RPM to 1152 RPM, yielding an increase of 147RVPM or 15%. Arising from these results, it is conclusive that the deployment of fuzzy logic controller in clutch actuation control of an electro-pneumatic clutch actuation system will improve efficiency in heavy-duty vehicles. Indeed, it will make remarkable impact in the smooth operation of heavy-duty vehicles and hence limit the attendant calibration problems and associated poor performances in clutch actuation.

KEYWORDS: *Actuation, control, calibration, fuzzy logic, transmission*

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1. Introduction

Heavy-duty vehicles are able to accomplish a given assignment by virtue of their ability to achieve rotary motions or torque. The engine torque requirements differ for different work needs, hence there is need to provide for mechanical amplifications. Gearing mechanisms are used in this respect. For smooth transitions between several gearing positions, clutch actuation mechanisms are introduced. The clutch acts as an isolator between the drive shaft linked to the engine and the driven shaft connected to the load (wheels) to safeguard the system from teeth grinding during the transition periods. The effectiveness and smoothness of the coupling of the drive and driven shafts in the midst of the gearing transition is a measure of the efficiency index of the clutch mechanism and power transmission between the engine and the load. The gear shift quality of a vehicle is an indicator for accessing how good a clutch system is (Li-kun*et al,* 2015). Clutching process is a control system mechanism for given instruction to the automobile or machine to operate. A clutch is a device applied to engage and disengage transmission of power particularly from a driving shaft to a driven shaft. It can also be said that a clutch ensures that the transmission link between the engine and the driven parts establishes a releasable torque (Mishra, 2014).Clutches and indeed brakes are therefore essential control elements for effective control and smooth transmission of drive torque, power and speed in many rotating drive systems. The piston position in the actuator chamber ultimately defines the amount of torque that a clutch system can transmit (Barma and Huba, 2015).

Actuation is important in any physical process that requires mechanical movement. Actuation process is a system that utilises its outputs to achieve a control action on a machine or device, with the ultimate aim of producing a linear or rotary motion. A device or element deployed for this purpose is an actuator(Carlos, 2016). Enhancement in clutch actuation control is critical for automobile developments. The present conventional control methods applied in the electrical control unit, appear inadequate owing to operational difficulties with heavy duty vehicles which often lead to failures on the road. The operational problems are associated with clutch systems in heavy-duty vehicles. Some of them are clutch wearing/burnt, torsional spring weakening, clutch vibrations, fibre rebating, and leakage in seals (Nice and Bryant 2019). Others are friction forces, weakening piston springs and weakening of clutch release bearing. There are also problems related to clutch diaphragm weakening and clutch sticking. To this end, Samson (2019) noted that wears are often seen in gear-based travel sensors. Clutch defects manifest in clutch actuation positional errors in actuation chambers which may lead to poor clutch engagement or disengagement.

The conventional electrical control design methods adopt off/on control, proportional control, servo mechanism control, integral control, and a combination of Proportional and Integral (PI) control in clutch actuation control. These design techniques allow for frequent calibration of clutch load as a means of ameliorating actuation problems and ensure better operation. Calibrations of clutch actuations are mandatory requirements after installation and or maintenance operations (Calibrating the clutch Actuator from Sachs Workshop Tips 2019). Calibration also ensures quicker responsiveness of the actuator control as well as manoeuvring driving situations in slick roads and launching on hilly terrain with heavy loads among others (Clutch Problems, Trouble Shooting and Service, 2019). Workshop Tips on Clutch from ZF Aftermarket on the topic Overview of all Workshop Tips on Clutches and repair Tips for Clutch System (2019) noted that failure in calibration among others are front with problems in clutch actuation. Clutch calibrations are accomplished in a number of ways. Some are achieved by disengaging the output or load shaft until when a reference engine or input shaft speed is reached. It can also be done by increasing the pressures on the actuator piston while monitoring the engine speed for a low torque transmission to the load shaft. Essentially, calibration entails variation in the fill time for clutch engagement and disengagement routines. It can result in the narrowing of the clutch travel distance in the actuator or by increasing pressure on the piston through the variation of the energizing current in the electrical control module of the clutch system (Li-kun*et al* 2015). The practices of calibration are often neglected by the machine operators; a neglect that leads to tales of woes. This neglect is also made worst by our poor attitude to maintenance.

There is need for a more dynamic control process to substitute the conventional control method. The new technique will be robust enough to checkmate weakening piston springs and weakening of clutch release bearings which are prominent faults responsible for piston positional error in clutch actuation

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and thereby eliminate the need for routine manual calibration. The substitution of intelligent agent-based controller modeled in a fuzzy logic technique in place of conventional controller is expected to be dynamic enough to handle this calibration problem and hence improve efficiency in heavy duty vehicles.

2. Basic Theory

When explanation to an idea, concept, process or anything lacked clarity or is indefinite, such explanation could be described as fuzzy. The concept of fuzzy ordinarily cannot be welcomed in normal life situations. However, when there are elements of logic backing a given idea, then it can find a place in engineering science. This is the situation in fuzzy logic and is applicable in control system designs. The fuzzy model relationship is stated in the form of ‘IF’ ‘THEN’ rules. This relationship is usually not clear, uncertain and ambiguous. Fuzzy logic paves the way for the study of inference process in which conclusions are implied and hence enables reasoning abilities of humans to be introduced in systems that are knowledge-based. The fundamental principles of fuzzy logic are a mathematical window for solving inherently unclear processes in human cognitive aspects involving basically thinking and reasoning (Fuller, 2001).The current conventional control approaches for addressing the problems of complex parameters and uncertainties in nonlinear systems have become inconvenient and grossly inadequate. The emergence of fuzzy logic and neural network control approaches in intelligent control applications have been adjudged most active, fruitful and acceptable in today’s control system research (Wu *et al*, 2005).The designs of fuzzy logic systems are relatively simple. The understanding and implementation of fuzzy logic systems are not necessarily reserved exclusively for experts in control theory. In the works of Babuska (2002), two major types of control rules are identified in fuzzy control applications. They are Mamdani model and the Takagi-Sugeno model. Ihedioha and Eneh (2015) concurs that Mandani and Takagi-Sugeno are the methods of control rules in fuzzy logic applications.

In Mamdani control, rules expressed in linguistic forms are prompted by instinct. Mandani thus adopted the rule format that something must happen(antecedent IF) before something else happens(consequent THEN). This is the popular “IF THEN” rule of fuzzy propositions. It can be defined thus:

R_i: If x is A_i then y is B_i; i= 1; 2;……… ; K :
Where ‘R_i’ stands for the rule, ‘A_i’ stands for the antecedents ‘IF’ and ‘B_i’ stands for the consequence ‘THEN’. The linguistic expression represents the fuzzy sets. The ‘K’ is the number of rules in the model. x and y are the input and output ports. The linguistic fuzzy model is mostly used for qualitative knowledge. Babuska (2002) agrees that Mamdani model is a typical model deployed for knowledge based and expert systems applications.

Takagi-Sugeno rules supports possible insertions, alterations or estimations of power terms in control rules. Takagi and Sugeno model are popular model in the identification of data in systems. In Takagi and Sugeno model, theexpression that something must happen(antecedent IF) is defined in the same way as in Mamdani model, but the difference is in the “before something else happens(consequent THEN)”. The linear function consequent aspect of the output undergoes some form of mathematical transformation (affine transformation) of the input variables. The Takagi and Sugeno model are defined thus:

R_i: If $\mathbf{x}$ is A_i theny_i= $\mathbf{a}^{Ti}$
$\mathbf{x} + b_i$; i= 1; 2; …….. ; K;

Where ‘R_i’ stands for the rule, ‘A_i’ stands for the antecedents ‘IF’ and is defined as the input fuzzy space where ‘$\mathbf{a}^{Ti}$’ is valid. The ‘K’ is the number of rules in the model. x is the input port while y is the output port. ‘$\mathbf{y}_i$’is a vector that defines the consequent parameter and ‘b_i’is a scalar off set in the input. This model is a combination of both linguistic expression and a reversion back to the earlier standard function. The ‘y’ is also the output computation that involves weighted average of the individual rules in the model.

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The Takagi and Sugeno model can also result in a more complex and confusing expression. The antecedent fuzzy sets are in most circumstances expressed in noticeable input boundaries that may often be extended. The input variables to the Takagi and Sugeno model are mere linear approximation of models of the nonlinear system under considerations (Babuska, 2002). The Takagi and Sugeno model can be described as a transformation of nonlinear function or a parameter scheduling model to a fair approximate linear model. The Author noted that the antecedent and consequent parameters may be unique. Furthermore, Ihedioha and Eneh (2015) noted comparatively that while Mandani method of control rule is ideal for expert knowledge in a human like manner, the Takagi-Sugeno method proves efficient in mathematical approach to optimization and adaptive techniques in tackling control problems. Fuzzy logic control design follows four stages of fuzzification, knowledge base (fuzzy rule), inference engine (reasoning) and defuzzification. Fig.1 illustrates.

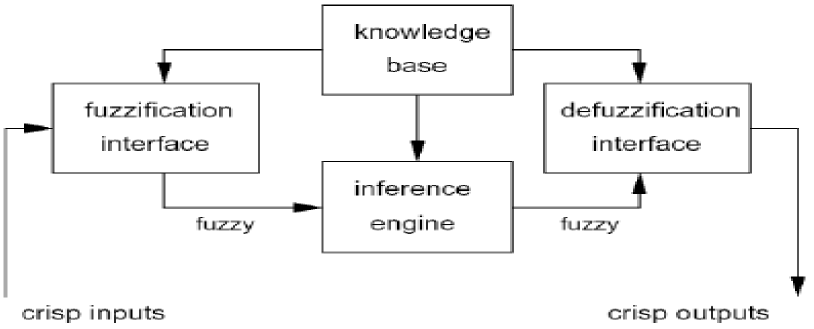

Fig. 1: Main components of a fuzzy system (Sharma, 2011)

An intelligent agent-based controller such as fuzzy logic controller can substitute conventional controller in a control process. Vernon, (2010) agrees that a conventional controller can be replaced with a fuzzy controller**.** This is illustrated in fig.2.

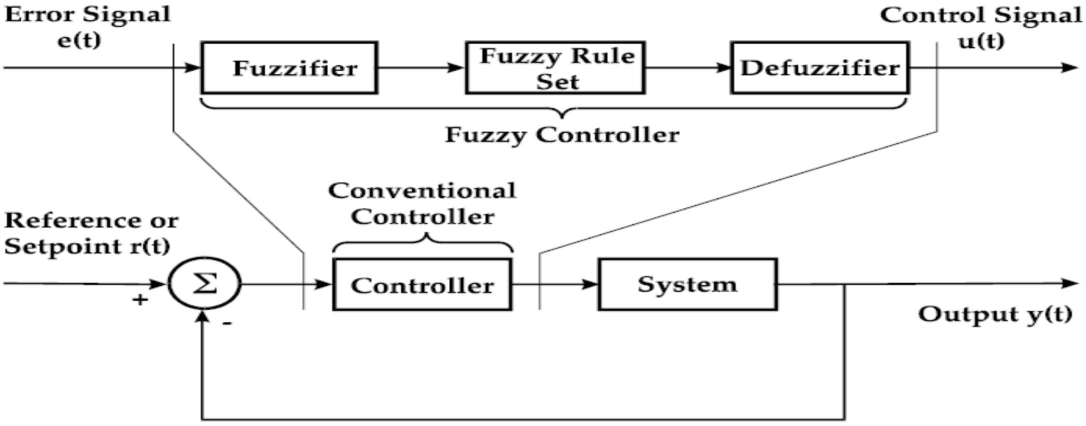

Fig. 2: Fuzzy controller adapted to replace a conventional controller (Vernon, 2010)

The concept of fuzzy ordinarily cannot be welcomed in normal life situations. However, when there are elements of logic backing a given idea, then it can find a place in Engineering science. This is the situation in fuzzy logic and is applicable in control system designs. Sharma (2011) agrees that the improved performance identified in the use of fuzzy logic approaches for some specific applications are the direct manifestation of the two main characteristics features of fuzzy systems. These characteristics are the suitability of Fuzzy systems for reasoning in circumstances that are not certain or can be estimated and the accommodation of approximated values in taking decisions in vague or unclear information. Fuzzy logic paves the way for the study of inference process in which conclusions are implied and hence enables reasoning abilities of humans to be introduced in systems that are knowledge-based. The emergence of fuzzy logic control approaches in intelligent control applications have been adjudged most active, fruitful and acceptable in today's control system research (Wu *et al*, 2005). Indeed, the introduction of fuzzy logic controller in electro-pneumatic clutch actuation control

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for heavy duty vehicles, will certainly eliminate the need for frequent calibration of its clutch system and hence reduce the attendant failures and accidents on our roads especially in hilly terrains. It is applied in this study.

3.0 Materials and Methods.

This section is devoted to the materials used in the study, the apparatus deployed and the procedure adopted in the study.

3.1 Materials.

The study materials for this work includes the actuation chamber, clutch plate, static and dynamic gearing parameters of a Mercedes Benz Actros Truck model MP 2, 2031from which conventional actuation parameters were sourced empirically. Fuzzy inference editor using MATLAB environment was explored in the fuzzy logic design while the fussy inference engine was introduced for pulling together of the respective degrees of memberships. The inference engine examines all the rules in the rules base and computes the weighted consequences of all the relevant degrees of firing into a single fuzzy set. The Root Sum Square (RSS) technique of computation is adopted in this presentation.

3.2 Methods.

3.2.1 Conventional Controller design

Empirical research method was used to obtain the initial data prevalent in the actuator chamber of an Actros Truck model MP 2, 2031. This formed the characterised conventional control data. The details of the characterisation are contained in the work of Ndubuisi*et el* (2023) entitled “Physiological Characterization of Electro-Pneumatic Clutch Actuation Control System for Heavy-Duty Vehicles”. A Simulink model for conventional controller was designed with MATLAB 7.5 system. Longitudinal vehicle dynamics building blocks were connected in the design. Subsystem building blocks for error, power, torque, speed and clutch travel parameters were connected. A data input/output subsystem where relevant analytical data for error, power, torque, speed and clutch travel parameters were fed and read, were also connected. The design is shown in figure 3.

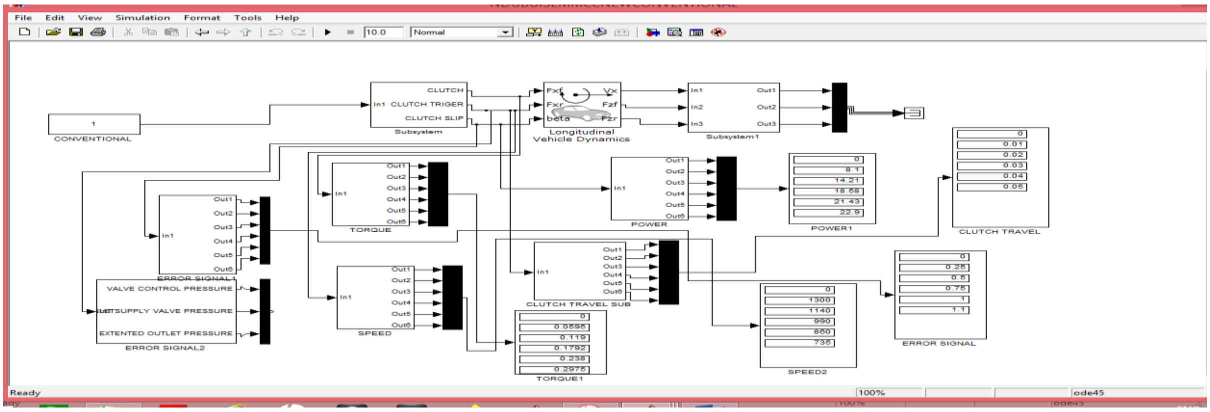

Fig. 3: Simulink Model for Conventional Controller

3.2.2 Fuzzy logic control design

Mandani Technique of Fuzzy inference editor in a MATLAB environment was explored in the development of a rule base for the actuation control of the electro electro-pneumatic clutch system. Seven input membership functions of fuzzy rules for positional error and change in positional error as inputs were designed. They are negative high (NH), negative medium (NM), negative low (NL), zero (Z), positive low (PL), positive medium (PM), and positive high (PH) respectively. Three output membership functions for sensor monitor as output gain were also designed. They are low (L), medium (M) and high (H) respectively. The rule base for the control mechanism, the actuator control sequence and the rules for the sequence were generated. The Mandani Technique of Fuzzy inference editor is

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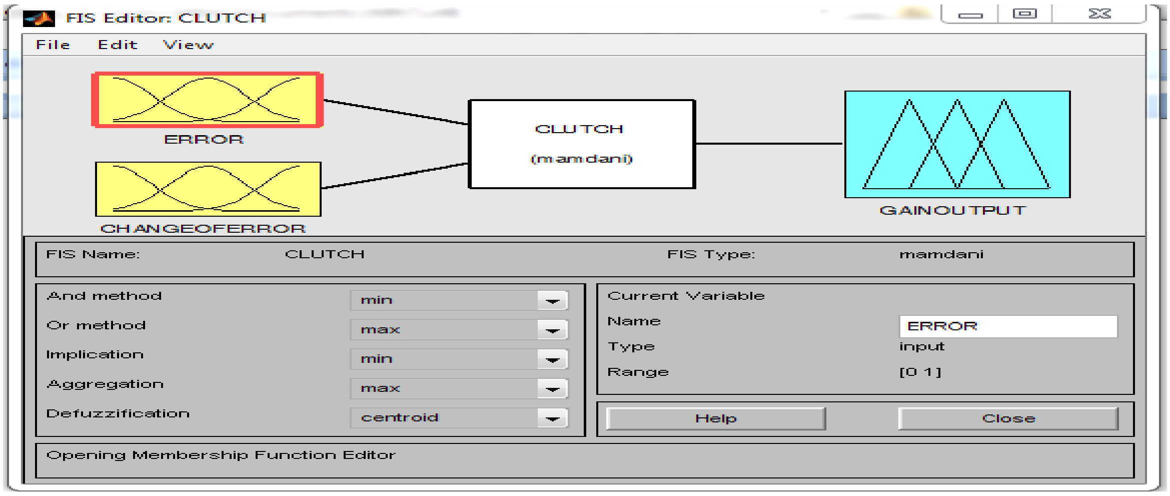
shown in fig.4 while the fort-nine rules generated is shown in table 1. The fussy rules are incorporated in a Simulink model where it was fed into a modeled conventional controller in a Simulink platform.



FIS Name: CLUTCH
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: ERROR
Type: input
Range: [0 1]
Opening Membership Function Editor

Fig. 4: Fuzzy inference editor for the design of fuzzy rule for an improved control of electro-pneumatic clutch actuation system

Table 1: Summary of the fuzzy rule.

S/N	ERROR	CHANGE IN ERROR	GAIN
1	NB	NB	LOW
2	NB	NM	LOW
3	NB	NS	LOW
4	NB	Z	LOW
5	NB	PS	LOW
6	NB	PM	LOW
7	NB	PB	LOW
8	NM	NB	LOW
9	NM	NM	AVERAGE
10	NM	NS	AVERAGE
11	NM	Z	AVERAGE
12	NM	PS	AVERAGE
13	NM	PM	AVERAGE
14	NM	PB	LOW
15	NS	NS	HIGH
16	NS	Z	HIGH
17	NS	PS	HIGH
18	NS	PM	HIGH
19	NS	PB	LOW
20	Z	NB	LOW
21	Z	NM	HIGH
22	Z	NS	HIGH
23	Z	Z	HIGH
24	Z	PB	HIGH
25	PS	NM	AVERAGE
26	PS	NS	HIGH
27	PS	Z	HIGH
28	PS	PS	HIGH
29	PS	PM	HIGH
30	PS	PB	LOW
31	PM	NB	LOW
32	PM	NM	AVERAGE
33	PM	NS	AVERAGE

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34	PM	Z	AVERAGE
35	PM	PS	AVERAGE
36	PM	PM	AVERAGE
37	PM	PB	AVERAGE
38	PB	NB	LOW
39	PB	NM	LOW
40	PB	NS	LOW
41	PB	Z	LOW
42	PB	PS	LOW
43	PB	PS	LOW
44	NB	NM	LOW
45	PB	NS	LOW
46	PB	Z	LOW
47	PB	PS	LOW
48	PB	PM	LOW
49	PB	PB	LOW

Simulink model for Fuzzy controller was also designed in a MATLAB 7.5 system and accordingly connected as in the conventional Simulink.The Fuzzy Simulink model controller was cascaded with the conventional control block and the outputs extracted from the output device. The fuzzy logic Simulink is shown in figure 5 below while the result of simulation is presented in table 3.

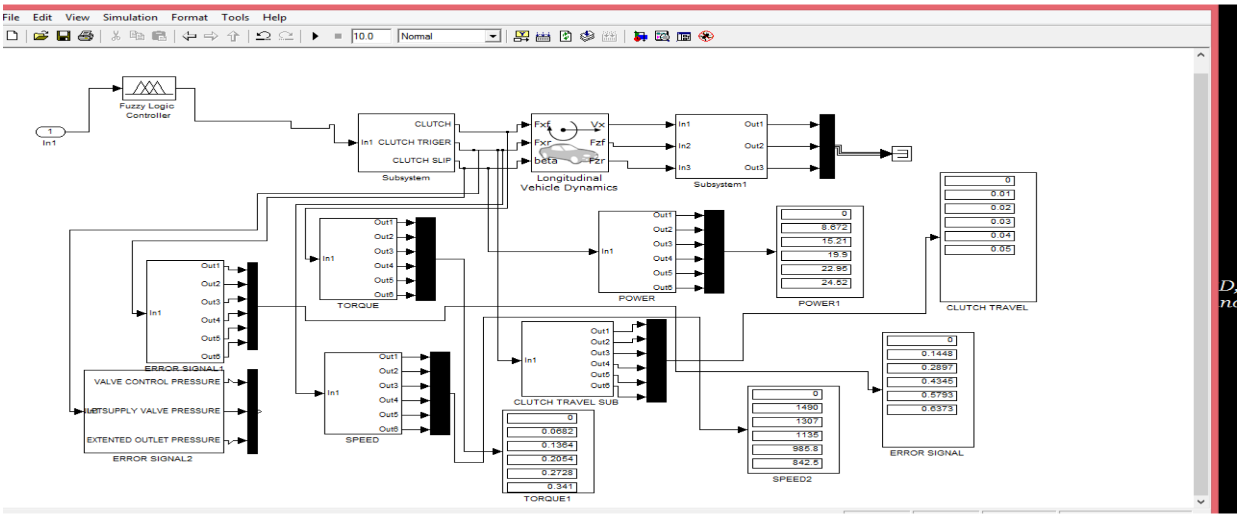

Fig. 5: Designed Simulink model of fuzzy logic controller for improved clutch actuation

4.0 Results and Discussions

4.1 Conventional and Fuzzy logic Simulink Data Presentation

The data obtained from the design of the Simulink model which is also the result of empirical study of the character of conventional controller for piston positional error, speed, torque and power respectively are presented in table 2 while the corresponding data from fuzzy logic controller is presented in table 3 below.

Table 2: Conventional Controller Simulink model data

Clutch travel (M)	Error signal (mm)	Speed (RPM)	Torque (NM)	Power (kw)
0	0	∞	0.0000	0.00
0.01	0.25	1300	0.0595	08.10
0.02	0.50	1140	0.1190	14.21
0.03	0.75	990	0.1792	18.58
0.04	1.00	860	0.2380	21.43

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0.05	1.10	735	0.2975	22.09

Table 3: Result obtained from fuzzy logic controller Simulink model

Clutch travel (M)	Error signal (mm)	Speed (RPM)	Torque (NM)	Power (kw)
0	0	∞	0.0000	0.00
0.01	0.1448	1490	0.0682	08.67
0.02	0.2897	1307	0.1364	15.21
0.03	0.4345	1135	0.2054	19.90
0.04	0.5793	985.8	0.2728	22.95
0.05	0.6373	842.5	0.3410	24.52

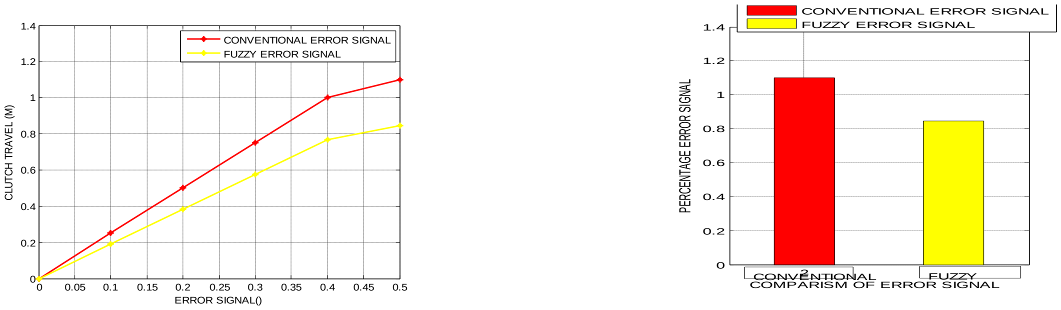
Table 3shows some levels of improvements over that of table 2.The results obtained from fuzzy logic controller shown in table 3are better comparatively with respect to that of conventional controller (characterized data) of table 2.To illustrate this further, each of the parameters of error, speed, torque and power are treated separately. The error comparison and analysis are presented in section 4.2. Similarly, angular speed comparisons as well as the analysis are also showcased in section 4.3. Sections 4.4 and 4.5are set aside for discussions on torque and power respectively.

4.2 Conventional and Fuzzy Logic Error Signals comparisons

Table 4 presents the analytical comparisons of the piston error signals as it moves in the actuation chamber during clutch engagent and disengagement process and the corresponding error signal readings recorded in both the conventional and fuzzy logic controllers. The trend of the readings are displaed in the graph of fig. 6 (a). Their averages are converted into percentages and presented in the barchart of fig. 6 (b). These results show a significant reduction of error in the fuzzy logic controller**.**Conventional controller data are shown in red colours while fuzzy logic controller data are in yellow colours for both graph and bar charts respectively. The same colour identifications are used for other parameters.

Table 4:Conventional and Fuzzy Logic Error Signals comparisons

Clutch travel (M)/Analysis	Conventional error signal(mm)	Fuzzy error signal (mm)
0	0	0
0.01	0.25	0.1448
0.02	0.50	0.2897
0.03	0.75	0.4345
0.04	1.00	0.5793
0.05	1.10	0.6373
Average	0.72	0.4171
% difference/base 100	100	57.93



(a) Graph (b) Bar Chart

Fig. 6: Conventional and Fuzzy Logic controller compared for error signal.

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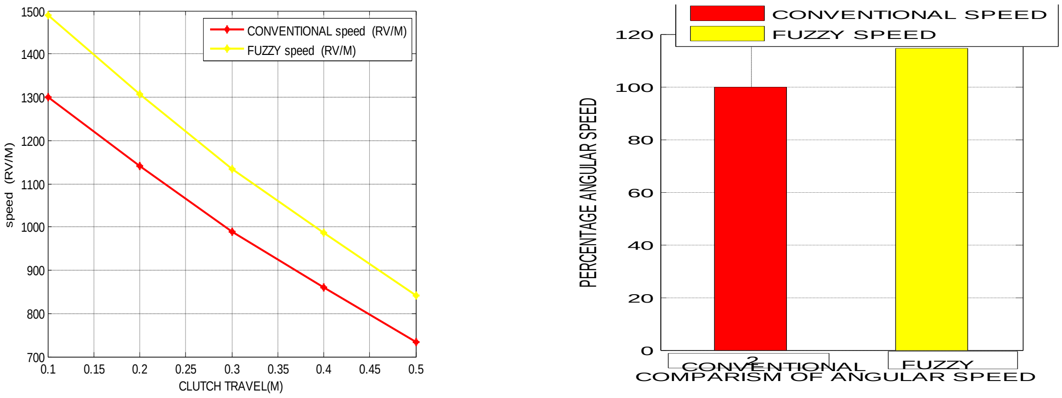
4.3: Conventional and Fuzzy Logic Angular Speed Comparisons.

In table 5, the analytical comparisons of the angular speed during the clutch actuation are presented for both the conventional and fuzzy logic controllers. The trend of the comparisons are displaed in the graph of fig. 7 (a), while their averages that are converted into percentages and presented in the barchart of fig. 7 (b) too. Significant improvementin the fuzzy logic controller is noticed**.**

Table 5:Conventional and Fuzzy Logic Angular Speed comparisons

Clutch travel (M)/Analysis	Conventional speed (RPM)	Fuzzy speed (RPM)
0.00	∞	∞
0.01	1300	1490
0.02	1140	1307
0.03	990	1135
0.04	860	985.8
0.05	735	842.5
Average	1005	1152.1
% difference/base 100	100	114.64



(a) Graph (b) Bar Chart

Fig. 7: Conventional and Fuzzy Logic controller compared for Speed

4.4: Conventional and Fuzzy Logic Engine Torque Comparisons

The analytical comparisons of the engine torque during the clutch actuation process recorded improvement in the fuzzy logic controller in contrast to that of the conventional controller. In table 6, the data are presented for both the conventional and fuzzy logic controllers. The trend of the comparisons are displaed in the graph of fig. 8 (a), while their averages are converted into percentages and presented in the barchart of fig. 8 (b) . The mprovementin the fuzzy logic controller is visible.

Table 6:Conventional and Fuzzy Logic Engine Torque comparisons

Clutch travel (M)/Analysis	Conventional torque (NM)	Fuzzy torque (NM)
0.00	0.0000	0.0000
0.01	0.0595	0.0682
0.02	0.1190	0.1364
0.03	0.1792	0.2054
0.04	0.2380	0.2728
0.05	0.2975	0.3410
Average	0.1786	0.2048
% difference/base 100	100	114.67

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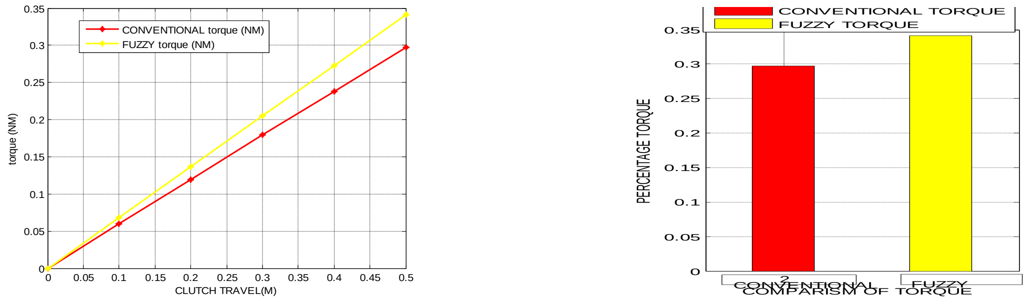


(a) Graph (b) Bar Chart

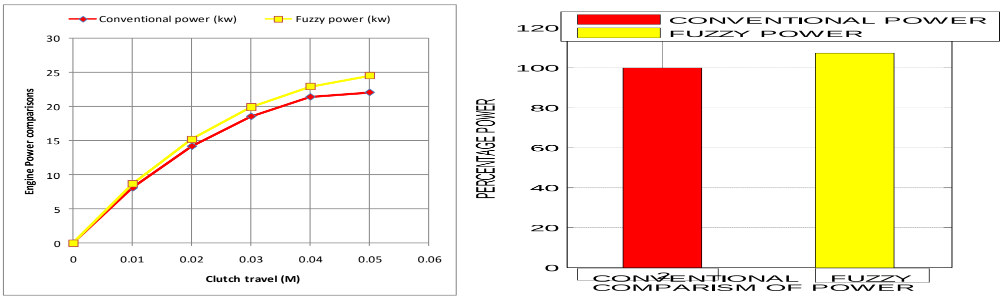
Fig. 8: Conventional and Fuzzy Logic controller compared for Torque

4.5: Conventional and Fuzzy Logic Engine Power Comparisons

Power produced in the conventiona controller and that of fuzzy logic controller are here conpared in table 6. The plot of the readings are displaed in the graph of fig. 9 (a). Their averages arecalculated and theier percentages were used to illustrae the difference. This is presented in the barchart of fig.9 (b). These results show that the fuzzy logic controller has advantage over conventional controller**.**

Table 7: Conventional and Fuzzy Logic Engine Power comparisons

Clutch travel (M)	Conventional power (kw)	Fuzzy power (kw)
0.00	0.00	0.00
0.01	08.10	08.67
0.02	14.21	15.21
0.03	18.58	19.90
0.04	21.43	22.95
0.05	22.09	24.52
Average	16.88	18.15
% Difference/ Base 100	100	108.12



(a) Graph (b) Bar Chart

Fig. 9: Conventional and Fuzzy Logic controller compared for Power

5.0 Conclusion.

From the above, it is shown that the average error for conventional controller was 0.72mm and the fuzzy logic controller gave 0.42mm. Error reduction of 0.3mm or 42%, proves that calibration challenges in clutching will be reduced comparably in heavy duty vehicles that utilizes fuzzy logic controller model in its actuation controls. The triple effect of this error reduction is felt in the engine module where increased engine torque, angular speed and power are recorded. The angular speed was increased from1005 RPM for conventional controller by 147 RPM or 15% to 1152 RPM level in a fuzzy logic controller. For the engine torque, average torque for conventional controller was 0.18NM

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while that of the fuzzy logic controller yielded 0.21NM. Thus, an increase in torque of 0.03NM or 15% was obtained. Lastly for the engine power, an average power for conventional controller was 16.88 watts while that of the fuzzy logic controller resulted in 18.25watts. Thus, an increase in engine power of 1.37watts or 8% was realized. All these results, transforms to an optimized performance, ease of operation and reduction in accidents that usually occurred with this class of vehicles especially on hilly terrains in a typical Nigerian highway. It is obvious that fuzzy logic controllers are indeed far better than conventional controllers in clutch actuation control of heavy-duty vehicle that utilizes electro-pneumatic method of transmission in its actuation process.

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Declarations

Author contribution statement

Ndubuisi, P.D.I.: Conceived and designed the experiments; Facilitated industrial collaboration; Contributed, materials, analysis tools; Wrote the paper.

Nwoke, O.N.: Performed the experiments; Analyzed and interpreted data; Wrote the paper.

Arua, J.E.: Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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