

DEVELOPMENT OF A VEHICLE ROBOTIC DRIVER WITH INTELLIGENT  
CONTROL SYSTEM MODELLING FOR AUTOMATED STANDARD  
DRIVING-CYCLE TESTS

AMMAR ABDO MOHAMMED MAHDI

A thesis submitted in  
fulfilment of the requirement for the award of the  
Degree of Master of Mechanical Engineering (by Research)

Faculty of Mechanical and Manufacturing Engineering  
Universiti Tun Hussein Onn Malaysia

SEPTEMBER 2019

*Specially dedicated to my great supervisor*

*To my beloved mother and father for their prayers and love during all my life*

*To my wife for her love and support*

*To my siblings for their support*



## ACKNOWLEDGEMENT

My deep and humble gratitude to ALLAH Almighty for providing the opportunity and giving me the strength to complete this work.

I would like to express heartiest thanks to my supervisor Dr. Wan Saiful-Islam Wan Salim who has persistently and determinedly assisted me during the whole course of this research. It would have been very difficult to complete this research without his enthusiastic support and insight.

I would like to take this time to thank Universiti Tun Hussein Onn Malaysia (UTHM) for the funding of this work through the Fundamental Research Grant Scheme (FRGS-1589).

Most importantly, I would like to thank my parents for their endless support throughout my life and for providing me the chance to reach this far in my studies. I thank them for having faith in me and always inspiring me and for their love and prayers.

My utmost thanks also go to my siblings and wife. Words cannot express how grateful I am to my family for all the support that they gave me throughout my academic journey. Without them, I might not be the person I am today.

Last but not least, my special gratitude is extended to all members of the Automotive Research Group (ARG) that has been my guidance and for giving the support I need for my research.

## ABSTRACT

New road vehicles are required to undergo several specific tests to meet the requirement set by governing bodies in various markets. These tests are often carried out over specific driving-cycles. To carry out lab-based driving-cycle tests, a typical vehicle manufacturer will employ a trained driver to follow driving profiles on a chassis dynamometer. This project involves development of a robotic driver controller for the automation of dynamometer-based vehicle testing according to industry standard driving cycle tests and produce repeatable results by replacing the traditional method of employing a human driver with a robot driver. The throttle and brake pedals control systems modelling and design for automatic transmission vehicle are implemented, with Fuzzy model reference adaptive control (Fuzzy MRAC) as the main controller. The vehicle model was developed using black-box modelling approach where simulations are performed based on real-time data and processed using Matlab System Identification tool. The Fuzzy MRAC was then designed within the simulations to attain the driving performance. The vehicle model response was sent as feedback to the robotic DC linear actuator motor which was modelled based on DC linear actuator motor design specification. The results obtained from simulation and modelling experiment were discussed and compared. The performed work concludes that system identification modelling with best fit accuracy of 79.93% can be applied in Fuzzy MRAC to ensure smooth and accurate vehicle driving pattern behavior even when the leading vehicle exhibits highly dynamic speed behavior during driving-cycle test. The performance of the vehicle model has shown an average 0.07 MSE for the throttle system and 0.008 MSE for the brake system of the vehicle model.

## ABSTRAK

Kenderaan jalan raya yang baru perlu melalui beberapa ujian spesifik untuk memenuhi syarat-syarat yang ditetapkan oleh perbagai badan pentadbiran dalam pasaran. Ujian-ujian ini biasanya dilaksanakan berdasarkan kitaran memandu tertentu. Untuk menjalani ujian kitaran memandu di makmal, pengilang kenderaan biasanya melantik pemandu terlatih untuk mengikuti profil pemanduan di atas dinamometer cesi. Projek ini melibatkan pembangunan pengawal pemandu robotik untuk automasi ujian kenderaan di atas dinamometer mengikut ujian kitaran pemanduan piawaian industri yang berupaya menghasilkan keberulangan keputusan yang baik dengan menggantikan kaedah tradisional, iaitu dari pemandu manusia kepada pemandu robotik. Rekabentuk dan pemodelan pengawal pedal pendikit dan pedal brek untuk kenderaan bertransimisi automatik dilaksanakan melalui kaedah Kawalan Rujukan Model Suai Fuzzy (Fuzzy MRAC) sebagai pengawal utama. Model kenderaan dihasilkan menggunakan pendekatan permodelan kotak hitam yang mana simulasinya dilakukan berdasarkan data masa nyata dan telah diproses menggunakan alat identifikasi sistem Matlab. Fuzzy MRAC kemudiannya direkabentuk dalam persekitaran simulasi untuk mendapatkan prestasi pemanduan. Tindak balas model kenderaan dihantar sebagai maklum balas kepada motor penggerak lurus DC robotik yang telah dimodelkan berdasarkan spesifikasi rekabentuk motor penggerak lurus DC. Dapatan keputusan daripada simulasi ujikaji permodelan telah dibincangkan dan dibandingkan. Hasil kerja yang telah dijalankan menyimpulkan bahawa permodelan identifikasi sistem dengan ketepatan penyuaian terbaik 79.93% boleh digunakan dalam Fuzzy MRAC untuk memastikan corak tingkahlaku pemanduan kenderaan yang tepat dan lancar walaupun ketika kenderaan yang diuji menunjukkan tingkahlaku kelajuan yang dinamik semasa ujian kitaran pemanduan. Prestasi kenderaan telah menunjukkan purata 0.07 MSE untuk system pendikit dan 0.008 MSE untuk system brek model kenderaan.

## TABLE OF CONTENTS

	<b>TITLE</b>	<b>i</b>
	<b>DECLARATION</b>	<b>ii</b>
	<b>DEDICATION</b>	<b>iii</b>
	<b>ACKNOWLEDGEMENT</b>	<b>iv</b>
	<b>ABSTRACT</b>	<b>v</b>
	<b>ABSTRAK</b>	<b>vi</b>
	<b>TABLE OF CONTENTS</b>	<b>vii</b>
	<b>LIST OF TABLES</b>	<b>xi</b>
	<b>LIST OF FIGURES</b>	<b>xiii</b>
	<b>LIST OF SYMBOLS</b>	<b>xviii</b>
	<b>LIST OF ABBREVIATIONS</b>	<b>xix</b>
	<b>LIST OF APPENDICES</b>	<b>xxi</b>
<b>CHAPTER 1</b>	<b>INTRODUCTION</b>	
	1.1 Introduction	1
	1.2 Research Background	1
	1.3 Problem Statement	3
	1.4 Research Objectives	5
	1.5 Research Scope	5
	1.6 Thesis Organization	6
<b>CHAPTER 2</b>	<b>LITERATURE REVIEW</b>	
	2.1 Introduction	8
	2.2 Fuel Combustion and Pollutant Emission	8
	2.3 Driving Cycle for Quantifying Vehicle Emissions	9
	2.3.1 Environmental Protection Agency: Federal Test Procedure (EPA: FTP-75).	10
	2.3.2 European Drive Cycle (ECE-15 & EUDC) and New European Drive Cycle (NEDC)	11
	2.3.3 Japanese Mode Cycles	12

2.3.4	Worldwide Harmonized Light Vehicles Test Procedure (WLTC)	13
2.3.5	Comparative Data of Standard Driving Cycles	16
2.4	Commercial Vehicle Robot Driver	17
2.4.1	Stahle SAP-2000 Robotic Driver	17
2.4.2	Horiba ADS 7000 Robotic Driver	19
2.5	Vehicle Robot Driver Control System	21
2.5.1	Review of Previous Research in Development of the Control System for Vehicle Robot Driver application	21
2.5.2	Adaptive Control System	23
2.5.3	Model Reference Adaptive Control	24
2.5.4	Fuzzy Logic Controller	26
2.5.5	Fuzzy Model Reference Adaptive Controller	29
2.6	System Identification	29
2.7	Vehicle Robot Driver Control Performance and Emission Evaluations	31
2.8	Summary of the Previous Related Works	31
2.11	Summary	34
<b>CHAPTER 3</b>		
<b>METHODOLOGY</b>		
3.1	Introduction	35
3.2	Project Overview	35
3.3	Robotic Driver Mechanical Design	37
3.3.1	Design Criteria and Requirement for Vehicle Robotic Driver	37
3.3.2	Motor Selection	38
3.3.3	Design of Vehicle Robotic Driver Assembly	40
3.4	Vehicle Modelling and System Identification	43
3.4.1	Experimental Setup	45
3.4.2	Load Cell Force Sensor	47

	3.4.3	Driving Cycle Model	49
	3.4.4	System Identification	50
	3.5	Controller Design	64
	3.5.1	Fuzzy Model Reference Adaptive Control (FMRAC) Design	64
	3.5.2	Fuzzy Logic Controller	67
	3.6	Vehicle Model Controller Design	71
	3.6.1	Reference Model Transfer Function	72
	3.6.2	Fuzzy Model Reference Adaptive Control Design	73
	3.7	Robotic Driver Model Controller Design	82
	4.7.1	DC Motor Modelling	82
	4.7.2	Robotic Driver Model	86
	3.8	System Performance Evaluation	91
	3.8.1	Rise Time	92
	3.8.2	Settling Time	92
	3.8.3	Percent Overshoot	92
	3.8.4	Mean Square Error (MSE)	93
	3.8.5	Root Mean Square Error (RMSE)	93
	3.8.6	Robot Driver Validation	93
	3.9	Summary	93
<b>CHAPTER 4</b>	<b>RESULTS AND DISCUSSION</b>		
	4.1	Introduction	94
	4.2	Vehicle Model Performance Analysis	94
	4.2.1	Fuzzy MRAC with Three Memberships Function Control Design for Vehicle Model	95
	4.2.2	Fuzzy MRAC with Seven Memberships Function Control Design for Vehicle Model	98
	4.3	Comparison Performance of Fuzzy MRAC with Three and Seven Membership's Function of Both System (Throttle And Brake Pedals)	101
	4.4	Robot Driver Model (DC Linear Actuator Motor) Performance Analysis	104



	4.4.1	Step Input Model Performance of the DC linear Actuator Motor	104
	4.4.2	Robustness Model Performance of DC Linear Actuator Motor	105
	4.5	Full Simulated System of the Vehicle Robot Driver	109
	4.6	Summary	110
<b>CHAPTER 5</b>		<b>CONCLUSIONS AND FUTURE RECOMMENDATIONS</b>	
	5.1	Introduction	111
	5.2	Conclusion	111
	5.2.1	Development of a Closed-Loop Controller Using Fuzzy Model Reference Adaptive Control (Fuzzy MRAC) (Objective I)	111
	5.2.2	Implementation and Testing of Fuzzy MRAC in the Design of a Robotic Driver (Objective II)	112
	5.3	Recommendations for Future Work	113
		<b>REFERENCES</b>	<b>114</b>
		<b>APPENDICES</b>	<b>122</b>



## LIST OF TABLES

Table	Title	Page
2.1	Summary of technical specifications of the WLTC classes	15
2.2	Summary of technical specifications of the WLTC Class 3-2	15
2.3	Comparison of the technical specifications between the NEDC, FTP-75, JC08 and WLTC Class 3-2	16
2.4	Stahle SAP-2000 Actuator Specs	18
2.5	Horiba ADS 7000 Actuator Spec	20
2.6	Summary of the Previous Related Works	31
3.1	Motor Selection	39
3.2	Linear Motor Specification:	39
3.3	Wiring connection of load cell sensor	49
3.4	Best fit, Final prediction error and Mean square error for all models	61
3.5	Fuzzy 3MRA controller rules for three membership function	75
3.6	Error input for three membership function	76
3.7	Change of error input for three membership function	77
3.8	The output for three membership function	77
3.9	Fuzzy 7MRA controller rules for seven membership function	78
3.10	Error input for three membership function	80
3.11	Change of error input for seven membership function	81
3.12	The output for seven membership function	82
3.13	Parameters variables of DC motor modelling circuit	83

3.14	DC linear actuator motor parameters	86
3.15	Fuzzy 3MRA controller rules for three membership function	89
3.16	Error input for three membership function	89
3.17	change of error input for three membership function	90
3.18	the output for three membership function	91
4.1	Analysis performance for Fuzzy 3MRAC of the throttle pedal	95
4.2	Analysis performance for Fuzzy 3MRAC of brake pedal	97
4.3	Analysis performance for Fuzzy 7MRAC throttle system	99
4.4	Analysis performance for Fuzzy 7MRAC of brake pedal controller	101
4.5	Performance Analysis for all the designed controller of the vehicle model	103
4.6	Performance evaluation for DC linear actuator motor position controller	104
4.7	Performance evaluation of set point tracking for DC linear actuator motor position controller (Fuzzy 3MRAC)	106



## LIST OF FIGURES

<b>Figure</b>	<b>Title</b>	<b>Page</b>
1.1	World Motor Vehicle Sales according to (OICA)	1
1.2	New European Drive Cycle	6
2.1	Constant Volume Sampling (CVS) layout	10
2.2	U.S. Emissions Test Driving Cycle for Light-Duty Vehicles (FTP- 75)	11
2.3	European Emissions Test Driving Cycle (ECE-15)	12
2.4	European Extra-Urban Driving Cycle (EUDC)	12
2.5	New European Driving Cycle (NEDC)	12
2.6	Speed profile of the Japanese 15 mode (J15) and 10-15 mode (J10-15) driving cycles	13
2.7	Speed profile of the Japanese 11-mode (J11) cycle employed for emissions measurement under cold starting, with identification of the various modes	13
2.8	Speed profile of the WLTC driving cycle; a downscaling procedure is applied to improve drivability for the cases of vehicles with PMR close to the borderlines between Class 2 and 3 or very low powered in Class 1	15
2.9	Timeline of test cycles employed for emission certification purposes in Europe, the U.S. (federal) and Japan	16
2.10	Stahle SAP-2000	18
2.11	Horiba ADS 7000	20
2.12	Adaptive control structure and adaptation scheme	24
2.13	Model Reference Adaptive Control System MIT rules	25
2.14	Fuzzy logic controller structure	27

2.15	Examples of membership functions	28
3.1	Project flowchart	36
3.2	Schematic diagram for development of an automated vehicle driving system for standard driving cycle studies	37
3.3	Robot driver design requirements consideration	38
3.4	Linear motor	39
3.5	(a) Isometric view, b) Side view, c) Front view, (d) Isometric view of the vehicle robot driver	41
3.6	Bottom view of the robot driver	41
3.7	Front and Isometric view of the vehicle robot driver	42
3.8	Isometric view of the robot driver	42
3.9	Fabricated robotic driver	42
3.10	System modelling overview	44
3.11	Workflow of the system modelling	44
3.12	The schematic diagram of the modelling process	45
3.13	Car installed on a chassis dynamometer	45
3.14	Load force sensor setup on the car pedals	46
3.15	Overall system architecture for experimental setup	46
3.16	Working principle of strain gauges	47
3.17	Load cell force sensor working principle	47
3.18	Strain gauge Wheatstone bridge	48
3.19	Hardware Installation of the load cell sensor with Hx711 model and Arduino microcontroller	49
3.20	European Emissions Test Driving Cycle (ECE-15)	50
3.21	One phase of European Emissions Test Driving Cycle (ECE-15)	50
3.22	The basic system identification procedure	51
3.23	Overview of the input and output data collection for the system identification	52
3.24	The applied force on the throttle pedal for NEDC driving pattern	56

3.25	The applied force on the brake pedal for NEDC driving pattern	56
3.26	The collected experiment speed from the vehicle	56
3.27	Input and output data for model estimation	57
3.28	Input and output data for model validation	57
3.29	System identification app GUI in Matlab	58
3.30	Measured and simulated model output	59
3.31	ARX model with automatic generated best fit of the system	60
3.32	Best fit graph for the system identification model	61
3.33	Residuals correlation analysis for First Order Model	62
3.34	Residuals correlation analysis for Second Order Model	62
3.35	Residuals Correlation Analysis for Third Order Model	63
3.36	Residuals correlation analysis for ARX model	63
3.37	Fuzzy MRAC flowchart design	64
3.38	Block diagram of MRAC MIT approach	65
3.39	Block diagram of Fuzzy MRAC	67
3.40	Block diagram of fuzzy logic controller	68
3.41	Mapping of controller step response to fuzzy rules	68
3.42	Fuzzy interface system	69
3.43	Controller block diagram	71
3.44	System setup block diagram	72
3.45	Block diagram of open loop test	72
3.46	Fuzzy MRAC design for vehicle model	74
3.47	Fuzzy 3MF with nine rules	75
3.48	Rule view in Matlab for Fuzzy 3MF	76
3.49	Error membership function for Fuzzy 3MRAC	76
3.50	Change of error membership function for Fuzzy 3MRAC	77
3.51	Output membership function for Fuzzy 3MRAC	77
3.52	Fuzzy 3MF Defuzzification block diagram	78
3.53	Rule view in Matlab for Fuzzy 7MF	79
3.54	Surface view of Fuzzy 7MRAC design	80
3.55	Error membership function for Fuzzy 7MRAC	80
3.56	Change of error membership function for Fuzzy 7MRAC	81

3.57	Output membership function for Fuzzy 7MRAC	82
3.58	DC motor system (a) Schematic diagram (b) Block diagram	83
3.59	(a) Relation between angular and linear movement (b) Free body diagram for the linear electrical actuator	85
3.60	Block diagram of open loop test	87
3.61	Fuzzy MRAC design for robot model (DC linear actuator motor)	88
3.62	Rule view in Mat lab for Fuzzy 3MRAC of DC Linear actuator motor	88
3.63	Surface View of the Fuzzy Designed for the Dc linear actuator motor	89
3.64	Error membership function for Fuzzy 3MRAC of Dc linear actuator motor	90
3.65	Change of error membership function for Fuzzy 3MRAC of DC linear	90
3.66	Output membership function for Fuzzy 3MRAC of DC linear actuator motor	91
3.67	Step response of performance evaluation	92
4.1	Allowable tolerance of vehicle speed and time based on NEDC	95
4.2	Fuzzy 3MRAC of vehicle speed with controlling the throttle pedal	96
4.3	Error performance between actual and reference for Fuzzy 3MRAC of throttle	96
4.4	Fuzzy 3MRAC of vehicle speed with controlling the brake pedal	97
4.5	Error performance between actual and reference for Fuzzy MRAC of brake pedal	98
4.6	Performance comparative Fuzzy 3MRAC of both system throttle and brake pedals	98
4.7	Fuzzy 7MRAC of vehicle speed with controlling the throttle pedal	99

4.8	Error performance between actual and reference for Fuzzy 7MRAC of throttle pedal	100
4.9	Fuzzy 7MRAC of vehicle speed with controlling the brake pedal	100
4.10	Error performance between actual and reference for Fuzzy 7 MRAC of brake pedal	101
4.11	The controller and human driver vehicle speed output comparison	102
4.12	MSE performance analysis for the Fuzzy MRAC with 3 and 7	103
4.13	MSE and RMSE performance values for the Fuzzy MRAC with	103
4.14	Step response for the DC linear actuator motor position controller (Fuzzy 3MRAC)	105
4.15	Error performance between actual and reference position for the DC linear actuator motor controller (Fuzzy 3MRAC)	105
4.16	Set point tracking response for the position of DC linear actuator motor controller (Fuzzy 3MRAC)	106
4.17	Error performance between actual and reference position for the DC linear actuator motor controller (Fuzzy 3MRAC) (a) Error for Set point tracking 30mm (b) Error for Set point tracking 50 mm	107
4.18	Simulink system of brake pedal position controller	108
4.19	Position output of the brake pedal controller	108
4.20	Position output vs applied force of the brake pedal	108
4.21	Simulink system of Throttle pedal position controller	109
4.22	Position output of the throttle pedal controller	109
4.23	Position output vs applied force of the throttle pedal	109



## LIST OF SYMBOLS

$e$	Error between the system and model outputs
$\frac{\delta e}{\delta \theta}$	Sensitivity derivative of the system
$-\gamma'$	Adaption gain
$\mu_A$	Membership function of A
$\mu_B$	Membership function of B
$U_i$	Centre of the output membership function
$T_r$	Settling time
$T_s$	Rise time
$\%OS$	Percentage overshoot
$\omega_n$	Natural frequency
$\zeta$	Damping ratio
$T$	Time
$y_1$	Actual value
$\tilde{y}_1$	Predicted value

**LIST OF ABBREVIATIONS**

MRAC	Model Reference Adaptive Controller
Fuzzy MRAC	Fuzzy Model Reference Adaptive Controller
Fuzzy 3MRAC	Fuzzy Model Reference Adaptive Controller With Three Membership Function
Fuzzy 7MRAC	Fuzzy Model Reference Adaptive Controller With Seven Membership Function
FLC	Fuzzy Logic Controller
MSE	Mean Square Error
RMSE	Root Mean Square Error
COG	Centre of Gravity
E	Error
CE	Change of Error
NEDC	New European Driving Cycle
ARX	Auto-Regressive with exogenous input
ARMAX	Autoregressive Moving Average with Exogenous Inputs
NB	Means Negative
NM	Means Negative Medium
NS	Means Negative Small
ZE	Means Zero Error

PS	Means Positive Small
PM	Means Positive Medium
PB	Means Positive Big



**LIST OF APPENDICES**

A	Setup and Arduino Programming Code for load cell calibration	122
B	Experiment Setup And Data Acquisition	127
C	Fabricated Vehicle Robot Driver	129
D	Vehicle driving-cycle calibration	131
E	System Identification Output for The Vehicle Model	133
F	List of Publications	135
G	Vitae	136



**PTTA UTHM**  
PERPUSTAKAAN TUNKU TUN AMINAH

# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction

This chapter introduces the study by giving a general overview of research background, problem statement, research objectives, scopes and outline of the thesis.

### 1.2 Research Background

The demand for transportation is expected to increase along with the increase in population and global economy. According to International Organization of Motor Vehicle Manufacturers (OICA) the world motor vehicle sales has increased to ninety seven millions vehicles in 2017 compared to ninety four millions vehicles in 2016, as can be observed in Figure 1.1.

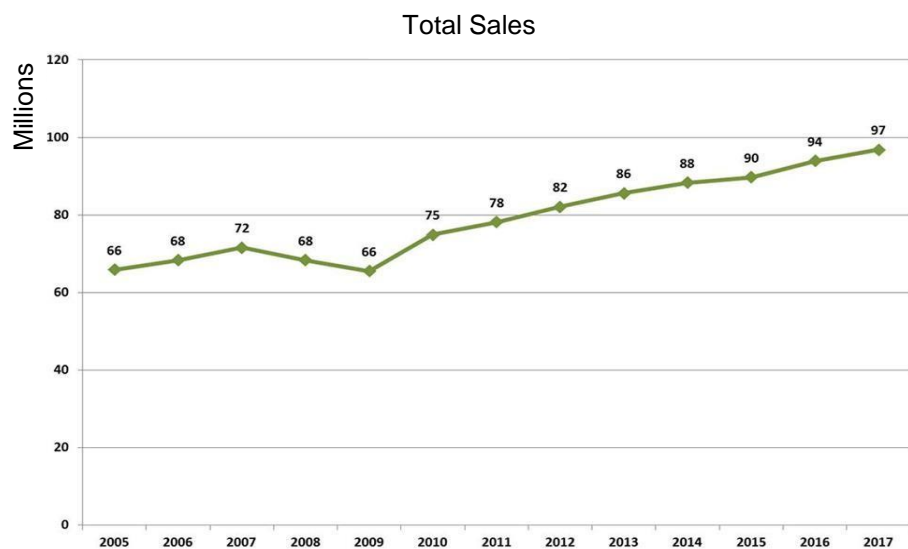


Figure 1.1 : World Motor Vehicle Sales according to (OICA) [1]

This rise of vehicles production will greatly impact the environment through three major areas, namely resource depletion, greenhouse emission and the local pollution. These are caused by the fuel combustion and emissions from cars, trucks, buses and other vehicle. The five major emissions produced by internal combustion engines are hydrocarbons (HC), Carbon Monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), Carbon Dioxide (CO<sub>2</sub>) and solid particulates [2].

The vehicle-related emissions are dangerous and hazardous to the human health and the environment. CO<sub>2</sub> emission relates directly to fuel consumption and can be reduced by increasing engine efficiency and electrification/hybridization of powertrains. The concentration of NO<sub>x</sub>, HC and CO in the exhaust gas can be reduced through fine-tuning of the engine operation and with advancement in modern powertrain technology [3]. Authorities worldwide are imposing strict regulations on CO<sub>2</sub> emission from road vehicles. Emissions from vehicles are measured over specific driving pattern called driving cycles which vary according to countries and regions [4]. Some examples of such driving cycles include Environmental Protection Agency: Federal Test Procedure (EPA: FTP-75) that is use in United States of America and the World Harmonized Light Vehicle Test Procedure (WLTP) driving cycle, and the outgoing New Europe Driving Cycle that is used in the Europe. Japan also has its own driving cycle which are the 10 modes, 10-15 modes and 11 modes test programs [5].

As the use of vehicles rapidly increase, the amount of pollution from the vehicle exhaust gas entering the atmosphere increases. To reduce this impact, stricter vehicle emissions and more stringent environmental protection laws are imposed on manufacturers. Today's automobile industry places improvement on energy consumption and emission levels as the primary areas for progress [6,7]. In order to launch a new car model, an automobile manufacturer has to ensure that it follows the applicable regulations and standards. With concern for the welfare of the environment, emission standards impose maximum allowable amount of pollutants a car can emit. In order to assess the pollutant emission rate of the certifiable vehicle, it has to perform a type-approval test cycle on a chassis dynamometer, where tailpipe gases are collected and analysed over standard driving cycles. To carry out emission tests, the automobile industry will employ dedicated drivers to drive their vehicle according to standard driving cycle on a chassis dynamometer. A driving cycle is a

fixed schedule of vehicle operation which allows an emission test to be conducted under reproducible conditions. Driving cycles are usually defined in terms of vehicle speed and gear selection as a function of time. Emission levels are dependent upon many parameters, including vehicle-related factors such as model, size, fuel type, technology level and mileage, and operational factors such as speed, acceleration, gear selection and road gradient. Not surprisingly, therefore, different driving cycles have been developed for different types of vehicle such as cars, vans, trucks, buses and motorcycles [5].

### 1.3 Problem Statement

To carry out an emission test, a typical manufacturer will employ a trained driver to follow the driving cycle on a chassis dynamometer. Current vehicle dynamometer emission test methods require trained and qualified personnel to perform repeated test cycles for long periods of time and a 'driver's aid' is provided to ensure that the driven cycle is as close as possible (e.g. within stated tolerances) to the defined standard driving cycle [5]. Having a driver conduct this test will subject the test to errors and even manipulation of test procedure besides inconsistent measurements which will require averaging of results over multiple tests. Thorough comparisons between robotic drivers and human drivers have shown that over-predict emission levels by 10-20% compared to human driver [8]. This can be attributed to differences in driving style. Human drivers tend to reduce the variation in acceleration by looking ahead of the current speed, hence obtaining smoother transitions between speed changes. This assists the comfort of the passengers. A robotic driver tends to closely follow the exact speed of the drive cycle, resulting in more frequent acceleration changes. In addition, experienced test-drivers acquire the skills to be able to drive closes to the minimum speed tolerance set by standard procedures thereby achieving lower emission levels. This manipulation and exploitation of test tolerance can be eliminated by having an automated system to conduct the driving cycles test.

This research is carried out to develop a robotic driver that is able to drive the vehicle based on standard driving cycles and replace the on-board human driver. The robotic driver is a combination of motors, hydraulic pumps, and actuators which are controlled via an advanced artificial intelligence control system with a closed loop

controller. Existing controllers in this application are based on traditional PID system which has displayed several disadvantages and exhibit varying degree of success in term of controller output accuracy. A simple conventional controller is not sufficient to deliver the required precision needed in driving cycle tests. This can be overcome by introducing a level of intelligence in the controller system. Therefore a control method that adapts the vehicle model and robotic driver to various driving pattern behaviours while maintaining system performance without parameter resets is needed. The Fuzzy Model Reference Adaptive controller (Fuzzy MRAC) is proposed in this study because the reference for the controller, which is the driving cycle is known input. In model reference adaptive control (MRAC) the system performance is given by the reference model and the tuning of controller parameters is based on the error, defined as the difference between reference model and real process responses. The main weakness of the standard MRAC is due to the presence of pure integral inside the adaptation law that will bring oscillation and instability in the Model Reference Adaptive Control controller output. To overcome this problem, the fuzzy logic controller is introduced in this study to replace the standard adaptive control in Model Reference Adaptive Controller. The fuzzy logic system obtains the desired output of the controlled object by regulating the adjustable parameters so that the output of the system under certain conditions can track the reference model output precisely [9,10]. Therefore, Fuzzy MRAC is suitable for applications in dynamic industrial control systems, where the influence of internal and external disturbances is high. As such, the Fuzzy MRAC has been selected as the controller of a robotic driver where the system can easily follow the reference standard driving cycle to achieve better accuracy and efficiency of standard driving cycle tests.

The automated vehicle driving system proposed in this study is used to drive the vehicle following the speed and time specified by the operator [7,11]. The idea is to replace the human driver with a robotic driver to carry out the driving cycle test. The purpose on eliminating human driver as a medium to drive the car is to reduce the error and inconsistencies that occur during driving cycle test [12,13]. This way, the drive cycle test can be carried out more efficiently. There are several disadvantages having a human as a driver to run the drive cycle test. The disadvantages include:

- vulnerability to human error.
- different reaction time.



## REFERENCES

- [1] Sales Statistics.OICA. Retrieved on September12, 2018, from <http://www.oica.net/category/sales-statistics/>.
- [2] W. W. Pulkrabek, “Summary for Policymakers,” in *Climate Change 2013 - The Physical Science Basis*, vol. 53, no. 9, Prentic Hall, 2013, pp. 1–30.
- [3] Alexandr Rosca. *Light Duty Vehicle Test Cycle Generation Based on Real-World Data*. Master thesis. Instituto Superior Técnico (IST); 2013.
- [4] P. Yuhui, Z. Yuan, and Y. Huibao, “Development of a representative driving cycle for urban buses based on the K-means cluster method,” *Cluster Computing*, pp. 10–12, Jan. 2018.
- [5] R. Kumar, P. Parida, S. Shukla, and W. Saleh, “MOVES model for idling emission of signalised junction in developing country,” *World Journal of Science, Technology and Sustainable Development*, vol. 12, no. 1, pp. 25–38, 2015.
- [6] S. Samuel, L. Austin, and D. Morrey, “Automotive test drive cycles for emission measurement and real-world emission levels - A review,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 2002.
- [7] H. Namik and T. Inamura, “Development of a robotic driver for vehicle dynamometer testing,” *Australasian Conference on Robotics*, pp. 1–9, 2006.
- [8] W. Thiel, S. Grof, G. Hohenberg, and B. Lenzen, “Investigations on Robot Drivers for Vehicle Exhaust Emission Measurements in Comparison to the Driving Strategies of Human Drivers,” *SAE International Fall Fuels and Lubricants Meeting and Exposition (San Francisco )*, vol. 19–22, 1998.
- [9] Z. Li, “Model reference adaptive controller design based on fuzzy inference system,” *Journal of Information and Computational Science*, vol. 8, no. 9, pp. 1683–1693, 2011.

- [10] M. Stankovic, M. Naumovic, S. Manojlovic, and S. Mitrovic, "Fuzzy model reference adaptive control of velocity servo system," *Facta universitatis - series: Electronics and Energetics*, vol. 27, no. 4, pp. 601–611, 2014.
- [11] N. Mizutani, Y. Ishida, H. Matsui, K. Yano, and T. Takahashi, "Automatic driving control by robotic driver considering the lack of a driving force at changing gears," *IEEE International Conference on Intelligent Robots and Systems*, vol. 2016–Novem, pp. 3075–3080, 2016.
- [12] P. Mock, J. Kühlwein, U. Tietge, V. Franco, A. Bandivadekar, and J. German, "The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU," *International Council on Clean Transportation*, vol. 2014–9, no, 2014.
- [13] G. Chen, W. G. Zhang, and X. N. Zhang, "Speed tracking control of a vehicle robot driver system using multiple sliding surface control schemes," *International Journal of Advanced Robotic Systems*, vol. 10, pp. 1–9, 2013.
- [14] Z. P. Zhu, A. M. Du, Z. X. Ma, W. Y. Zhang, and C. G. Fan, "Vehicle Robot Driver Research and Development Based on Servo Motor Control," *Applied Mechanics and Materials*, vol. 709, pp. 272–275, 2014.
- [15] N. G. Musthaq Ahamed PA, "Reduction of Carbon Monoxide Emission during Idling in 4-stroke Spark-ignition Engined Vehicle Using Scrubber," *International Journal of Engineering Research and Technology* vol. 6, pp. 469-476, 2013.
- [16] S. Samuel, L. Austin, and D. Morrey, "Automotive test drive cycles for emission measurement and real-world emission levels - A review," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 216, no. 7, pp. 555–564, 2002.
- [17] R. I. Larsen, "AIR POLLUTION FROM MOTOR VEHICLES," *Annals of the New York Academy of Sciences*, vol. 136, no. 12 Air Pollutio, pp. 277–301, Nov. 1966.
- [18] E. G. Giakoumis, "Light-Duty Vehicles," in *Driving and Engine Cycles*, Cham: Springer International Publishing, 2017, pp. 65–166.
- [19] Emission Test Cycles (2013). Dieselnet.com. Retrieved on December 09, 2018, from [https://www.dieselnet.com/standards/cycles/ece\\_eudc.php](https://www.dieselnet.com/standards/cycles/ece_eudc.php).

- [20] Global Technical Regulations (GTRs) (2014). E. Union. Retrieved on December 20, 2018, from <https://ec.europa.eu/docsroom/documents/25343/attachments/1/translations/en/renditions/native>
- [21] M. Tutuianu et al., “Development of the World-wide harmonized Light duty Test Cycle (WLTC) and a possible pathway for its introduction in the European legislation,” *Transportation Research Part D: Transport and Environment*, vol. 40, pp. 61–75, 2015.
- [22] Robot Drivers, Retrieved on December 09, 2018, from <https://www.staehle-robots.com/english-1/products/robot-drivers/>.
- [23] M. C. Johnson and. Development of a Robotic Vehicle Control System. Ph.D. Thesis. McMaster University, 2013.
- [24] ADS-7000. HORIBA. Retrieved on December 09, 2018, from [https://www.horiba.com/en\\_en/products/detail/action/show/Product/ads-7000-75](https://www.horiba.com/en_en/products/detail/action/show/Product/ads-7000-75).
- [25] M. Gopal and V. Singh, “Control Systems Engineering,” *IEEE Transactions on Systems, Man, and Cybernetics*, vol. SMC-6, no. 9, pp. 656–656, 2008.
- [26] P. Ioannou and Z. Xu, “Throttle and Brake Control Systems for Automatic Vehicle Following,” *I V H S Journal*, vol. 1, no. 4, pp. 345–377, 1994.
- [27] N. Wong, C. Chambers, K. Stol, and R. Halkyard, “Development of a robotic driver for autonomous vehicle following,” *International Journal of Intelligent Systems Technologies and Applications*, vol. 8, no. 1/2/3/4, p. 276, 2009.
- [28] K. Muller and W. Leonhard, “Computer control of a robotic driver for emission tests,” in *International conference on Industrial Electronics, Control, Instrumentation, and Automation (San Diego)*, 2003, pp. 1506–1511.
- [29] A. Moriyama, I. Murase, A. Shimosono, and T. Takeuchi, “A Robotic Driver on Roller Dynamometer with Vehicle Performance Self Learning Algorithm,” in *SAE Technical Paper Series*, 2010, vol. 1, pp. 42–54.
- [30] S. Sailer, M. Buchholz, and K. Dietmayer, “Driveaway and braking control of vehicles with manual transmission using a robotic driver,” in *Proceedings of the IEEE International Conference on Control Applications*, 2013, pp. 235–240.

- [31] G. Chen and W. Zhang, "Hierarchical Coordinated Control Method for Unmanned Robot Applied to Automotive Test," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 2, pp. 1039–1051, 2016.
- [32] G. Chen, W. G. Zhang, and X. N. Zhang, "Speed tracking control of a vehicle robot driver system using multiple sliding surface control schemes," *International Journal of Advanced Robotic Systems*, vol. 10, 2013.
- [33] Z. P. Zhu, A. M. Du, Z. X. Ma, W. Y. Zhang, and C. G. Fan, "Vehicle Robot Driver Research and Development Based on Servo Motor Control," *Applied Mechanics and Materials*, vol. 709, pp. 272–275, 2014.
- [34] J. Schwartz. Design of an Automobile Accelerator/Brake Pedal Robot for Advanced Driver Assistance Systems. Master Thesis. Purdue University, 2017.
- [35] S. Y. Kim, D. H. Lee, H. T. An, S. H. Lee, Y. H. Koh, and M. H. Lee, "Performance analysis of UPS(Ultrasonic Positioning System) using DGPS," in *IECON Proceedings (Industrial Electronics Conference)*, 2004, vol. 1, pp. 609–613.
- [36] W. Black, P. Haghi, and K. Ariyur, "Adaptive Systems: History, Techniques, Problems, and Perspectives," *Systems*, vol. 2, no. 4, pp. 606–660, Nov. 2014.
- [37] H. Anfinsen and O. M. Aamo, "Model reference adaptive control," in *Communications and Control Engineering*, Springer, Cham, 2019, pp. 227–253.
- [38] P. Jain and N. M.J, "Design of a Model Reference Adaptive Controller Using Modified MIT Rule for a Second Order System," *Advance in Electronic and Electric Engineering*, vol. 3, no. 4, pp. 477–484, 2013.
- [39] S. Pankaj and J. S. Kumar, *Biotechnology in Animal Husbandry*, vol. 5, no. 4. 2002.
- [40] S. Rogers, "Model reference adaptive control: From theory to practice," *Control Engineering Practice*, vol. 2, no. 6, pp. 1092–1093, 2003.
- [41] T. J. Ross and Timothy J. Ross, *Fuzzy Logic With Engineering Applications*, vol. 91. 2017.
- [42] I. Iancu, "A Mamdani Type Fuzzy Logic Controller," in *Fuzzy Logic - Controls, Concepts, Theories and Applications*, InTech, 2012.
- [43] J. Krejčí, "Fuzzy set theory," in *Studies in Fuzziness and Soft Computing*, vol. 366, 2018, pp. 57–84.

- [44] M. N. McAllister, "Fuzzy Logic with Engineering Applications (Timothy Ross)," *SIAM Review*, vol. 38, no. 1, pp. 174–175, 2005.
- [45] MathWorks, "Fuzzy Logic Toolbox™ User's Guide R2018b," 2017.
- [46] Y. Bai and D. Wang, "Fundamentals of fuzzy logic control — fuzzy sets, fuzzy rules and defuzzifications," in *Advances in Industrial Control*, 2006.
- [47] H. K. Lam and F. H. F. Leung, "Sampled-data fuzzy controller for time-delay nonlinear systems: Fuzzy-model-based LMI approach," *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, vol. 37, no. 3, pp. 617–629, 2007.
- [48] H. Ying, "Introduction to Fuzzy Control and Modeling," in *Fuzzy Control and Modeling*, 2010, pp. 1–5.
- [49] N. Mohammad, A. Munassar, and A. Govardhan, "A Comparison between Five Mod Mohammad, N., Munassar, A., & Govardhan, A. (2010). A Comparison between Five Models of Software Engineering. *International Journal of Computer Science Issues*, vol. 7, no. 5, pp. 94–101, 2010.
- [50] Z. Li, "Model reference adaptive controller design based on fuzzy inference system," *Journal of Information and Computational Science*, vol. 8, no. 9, pp. 1683–1693, 2011.
- [51] M. Stankovic, M. Naumovic, S. Manojlovic, and S. Mitrovic, "Fuzzy model reference adaptive control of velocity servo system," *Facta universitatis - series: Electronics and Energetics*, vol. 27, no. 4, pp. 601–611, 2014.
- [52] J. S. Dureja, V. K. Gupta, V. S. Sharma, M. Dogra, and M. S. Bhatti, "A review of empirical modeling techniques to optimize machining parameters for hard turning applications," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 230, no. 3, pp. 389–404, 2016.
- [53] R. G. K. M. Aarts. *System Identification and Parameter Estimation exercises*. Ph.D. Thesis. Universiteit Twente, 2012.
- [54] J. Schoukens, J. Suykens, and L. Ljung, "Technical report from Automatic Control at Linköpings universitet Wiener-Hammerstein Benchmark," 2009.
- [55] M. C. Campi and E. Weyer, "Finite sample properties of system identification methods," *IEEE Transactions on Automatic Control*, vol. 47, no. 8, pp. 1329–1334, 2002.

- [56] P. Suraj and P. Sandeep. A Study of Impulse Response System Identification. Master Thesis. Karlstads universitet; 2014.
- [57] L. Ljung, H. Hjalmarsson, and H. Ohlsson, “Four Encounters with System Identification,” *European Journal of Control*, vol. 17, no. 5–6, pp. 449–471, 2011.
- [58] Simrock, S. Control theory. DESY, Hamburg, Germany. 2008.
- [59] M. Gopal and V. Singh, “Control Systems Engineering,” *IEEE Transactions on Systems, Man, and Cybernetics*, vol. SMC-6, no. 9, pp. 656–656, 2008.
- [60] N. Mizutani, Y. Ishida, H. Matsui, K. Yano, and T. Takahashi, “Automatic driving control by robotic driver considering the lack of a driving force at changing gears,” in *IEEE International Conference on Intelligent Robots and Systems*, 2016.
- [61] N. Hirata, N. Mizutani, H. Matsui, K. Yano, and T. Takahashi, “Fuel consumption in a driving test cycle by robotic driver considering system dynamics,” in *Proceedings - IEEE International Conference on Robotics and Automation*, 2015, vol. 2015–June, no. June, pp. 3374–3379.
- [62] N. Mizutani, H. Matsui, K. Yano, and T. Takahashi, “Vehicle Speed Control by a Robotic Driver Using an Internal Model Control Considering Parametric Variations of a Vehicle,” *Journal of the Robotics Society of Japan*, vol. 33, no. 10, pp. 818–825, 2016.
- [63] G. Chen and W. G. Zhang, “Design of prototype simulation system for driving performance of electromagnetic unmanned robot applied to automotive test,” *Industrial Robot*, 2015.
- [64] N. Mizutani, H. Matsui, K. Yano, and T. Takahashi, “Vehicle speed control by a robotic driver considering vehicle dynamics for continuously variable transmissions,” *Journal of Robotics and Mechatronics*, 2018.
- [65] G. Chen, W. G. Zhang, and X. N. Zhang, “Speed tracking control of a vehicle robot driver system using multiple sliding surface control schemes,” *International Journal of Advanced Robotic Systems*, 2013.
- [66] L. Ljung, “Black-box Models from Input-output Measurements,” *IEEE Instrumentation and Measurement*, 2001.

- [67] T. Schulze and J. Weber, "Model Based System Identification for Hydraulic Deep Drawing Presses," in Proceedings of 15th Scandinavian International Conference on Fluid Power, Fluid Power in the Digital Age, SICFP'17, June 7-9 2017 - Linköping, Sweden, 2017, vol. 144, pp. 69–79.
- [68] Strain Gauges (2018). Allaboutcircuits. Retrieved on January 1, 2019, from <https://www.allaboutcircuits.com/textbook/direct-current/chpt-9/strain-gauges/>.
- [69] Getting Started with Load Cells (2018).sparkfun. Retrieved on January 1, 2019, from <https://learn.sparkfun.com/tutorials/getting-started-with-load-cells>.
- [70] M. M. Hassan, A. A. Aly, and A. F. Rashwan, "Different Identification Methods With Application To A Dc Motor," Journal of Engineering, Sciences, vol. 35, no. 6, pp. 1481–1493, 2007.
- [71] MathWorks, "System Identification Toolbox™ User's Guide," U.S., 2015.
- [72] J. K. Huusom, N. K. Poulsen, S. B. Jørgensen, and J. B. Jørgensen, "ARX-model based model predictive control with offset-free tracking," Computer Aided Chemical Engineering, vol. 28, no. C, pp. 601–606, 2010.
- [73] S. J. Dodds, "Plant Modelling," in Springer, no. 9781447166740, Springer International Publishing, 2015, pp. 73–167.
- [74] Driankov, D., Hellendoorn, H., & Reinfrank, M. An introduction to fuzzy control. Springer Science & Business Media, 2013.
- [75] Slotine, Applied Nonlinear Control Slotine. Englewood Cliffs, NJ: Prentice-Hall. 1991.
- [76] Munadi, M. A. Akbar, T. Naniwa, and Y. Taniai, "Model Reference Adaptive Control for DC motor based on Simulink," in Proceedings - 2016 6th International Annual Engineering Seminar, InAES 2016, 2017, pp. 101–106.
- [77] Sharaf, Soliman, Mansour, Kandil, and El-Shafii, "Laboratory implementation of artificial neural network speed controller for a rectifier fed separately excited DC motor," in Proceedings of Canadian Conference on Electrical and Computer Engineering CCECE-94, 1994, pp. 85–88 vol.1.
- [78] S. Nikhil Shewale and R. Deivanathan, "Modelling and analysis of dc motor actuator for an electric gripper," Journal of Engineering Science and Technology, vol. 13, no. 4, pp. 862–874, Apr. 2018.
- [79] Munadi and M. A. Akbar, "Simulation of fuzzy logic control for DC servo motor using Arduino based on MATLAB/Simulink," in Proceedings of 2014

International Conference on Intelligent Autonomous Agents, Networks and Systems, INAGENTSYS 2014, 2015, pp. 42–46.

- [80] T. S. Ng, “Mechatronics,” in *Studies in Systems, Decision and Control*, vol. 65, Springer International Publishing, 2016, pp. 27–38.
- [81] E. D. Ruiz-Rojas, J. L. Vazquez-Gonzalez, R. Alejos-Palomares, A. Z. Escudero-Uribe, and J. R. Mendoza-Vázquez, “Mathematical model of a linear electric actuator with prosthesis applications,” in *Proceedings - 18th International Conference on Electronics, Communications and Computers, CONIELECOMP 2008*, 2008, pp. 182–186.
- [82] J. R. Mendoza-Vázquez, E. Tlelo-Cuautle, J. L. Vázquez-Gonzalez, and A. Z. Escudero-Uribe, “Simulation of a parallel mechanical elbow with 3 DOF,” *Journal of Applied Research and Technology*, vol. 7, no. 2, pp. 113–123, Aug. 2009.
- [83] B. J. Shim, K. S. Park, J. M. Koo, and S. H. Jin, “Work and speed based engine operation condition analysis for new European driving cycle (NEDC),” *Journal of Mechanical Science and Technology*, vol. 28, no. 2, pp. 755–761, 2014.

