

**DEVELOPMENT OF DRIVING CYCLES AND A
MATHEMATICAL MODEL FOR FUEL ECONOMY
CHARACTERIZATION OF LIGHT DUTY VEHICLES
IN SRI LANKA**

Surath Gajanayake

198099f

Degree of Doctor of Philosophy

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

June 2024

DECLARATION

“I declare that this is my own work, and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Name of the Candidate: S.P. Gajanayake

Signature:

Date: 09/06/2024

The supervisor/s should certify the thesis/dissertation with the following declaration.

The above candidate has carried out research for the Masters/MPhil/PhD thesis/Dissertation under my supervision.

Name of the main supervisor: Dr A.G.T. Sugathapala

Signature of the supervisor:

Date : 12/08/2024

Name of the main co-supervisor: Prof. J.M.S.J. Bandara

Signature of the supervisor:

Date : 12.08.2024

ABSTRACT

Estimating the fuel consumption of vehicles under varying driving patterns is challenging and lacks a clear theoretical base. The study aims to provide a scientific basis for a better understanding of driving patterns and their influence on the fuel economy performance of in-use light duty vehicles in Sri Lanka. The study encompasses two specific objectives: the development of driving cycles to represent the local driving conditions of selected vehicle types and the development of a mathematical model capable of estimating fuel economy values of different light duty vehicle types under varying driving patterns. The methodology adopted during the study comprises the theoretical development of two local driving cycles: one specifying both 2W and 3W and the other specifying the characteristics of 4W and the development of a mathematical model that can estimate fuel economy values under varying driving conditions. The main findings of the study portray the characteristics of the two driving cycles developed for the Colombo Metropolitan Area: one cycle spans a period of 1499s which is developed to mimic the driving behavior of 4W whereas the other cycle spans a period of 1215s which is dedicated for 2W and 3W. When developing the said two cycles, data has been acquired from 19 major routes comprising 72 route links within the Colombo Metropolitan region. The micro-trip-based method is opted when developing driving cycles. Krigging spatial interpolation has been utilized as the classification technique for micro-trip generation. The mathematical model developed for the fuel economy characterization is undergone two-way validation, i.e., simulation-based validation and the validation based on manufacturer's data. When validated, the estimation accuracy of the model gets converged to a band between 89.61% to 92.78%. Conclusively, it can be stated that the developed and validated theoretical model can be utilized as a tool to estimate the fuel consumption of different vehicle types under varying driving conditions. Furthermore, it is recommended to refer to the local driving cycles developed to mimic the local driving behavior when using the theoretical model for localized fuel consumption estimations.

DEDICATION

To my beloved parents, Dr. Damayantha Gajanayake and Dr. (Mrs.) Geethani Gajanayake and to my beloved brother, Dr. Sarith Gajanayake.

ACKNOWLEDGEMENT

First and foremost, I am deeply grateful to my supervisors Dr Thusitha Sugathapala and Senior Prof. Saman Bandara for providing me with this opportunity, and for introducing me to this fascinating field of sustainable mobility. I would like to thank both of my mentors for their excellent supervision, supportiveness, encouragement, endless dedication, and guidance throughout my PhD. I have greatly benefited from their keen research insight and scientific rigour, and the work provided in this thesis would not have been possible without their support.

Secondly, I would like to thank Dr, Rasika Perera, the Chairman of my PhD progress review committee, who did provide extremely significant constructive reviews on my work which helped me to mold the research accordingly.

Thirdly, I wish to extend my gratitude to Dr Dimantha De Silva for providing me with accessibility to the necessary data acquisition tools for route selection.

Fourthly, I would like to thank the research coordinator of the Department of Mechanical Engineering, Dr Nalaka Samaraweera for guiding me in the administrative work of the PhD.

Last, but not least, I would like to thank my beloved wife and my beloved parents for encouraging me to pursue postgraduate studies and for supporting me throughout my journey.

CONTENTS

1.	INTRODUCTION	1
1.1	Motivation	1
1.2	Aim and Objectives.....	2
1.3	Scope of the Study	2
1.4	Methodology	3
1.5	Significance of the Research Study.....	3
2.	LITERATURE REVIEW	5
2.1	Literature review on the factors affecting the fuel consumption of LDVs.	11
2.2	Literature review on the driving cycle development.....	29
2.2.1	The rationale for the development of unique driving cycles for two-wheelers, three-wheelers, and four-wheelers	43
2.3	Literature review on auxiliary engine loads.....	52
2.4	Literature review on converting performance values (fuel consumption/emissions) from one driving cycle to another.	55
2.5	Summary	59
3.	METHODOLOGY	61
3.1	Route selection strategy	62
3.2	Data collection strategy.....	65
3.3	Cycle construction strategy	72
3.3.1	Cycle construction strategy for two-wheelers and three-wheelers.	74
3.3.2	Cycle construction strategy for four-wheelers.	76
3.4	Cycle validation strategy.....	78
3.5	Methodology for estimating the power demand of engine auxiliaries.	79

3.5.1	Modelling and Estimating the Power Demand of an Automotive Air Conditioner	80
•	Modelling of Metabolic Load	80
•	Modelling of Ambient Load	86
•	Modelling of Radiation Load	90
•	Modelling of Exhaust Load.....	92
•	Modelling of Engine Load	93
•	Modelling of Ventilation Load	95
3.5.2	Estimating the power demand of an automotive alternator	98
3.5.3	Estimating the power demand of other engine auxiliaries	100
•	Chapter Conclusion.....	102
3.6	Methodology for determining the theoretical model for fuel consumption estimation	104
4.	RESULTS AND VALIDATION	113
4.1	Results and validation of the driving cycles developed for 2W and 3W	113
4.2	Results and validation of the driving cycles developed for 4W.....	121
4.3	Representative driving cycles' validation against the regional driving cycles.	125
4.4	Results and validation of the theoretical model developed.....	128
4.5	Results of simulation tests: Simulation-based validation	131
4.6	Validation against the manufacturers' test data.	133
4.7	Results of driving cycle data tested on the developed model and the development of driving cycle conversion factors.	134
5.	CONCLUSIONS AND FUTURE DIRECTIONS.	151
5.1	Objective 1: Development of local driving cycles to mimic the local driving behaviour.	151

5.2	Objective 2: Development of the theoretical model for fuel consumption characterization.....	153
5.3	Discussion of limitations of the study	155
5.4	Concluding remarks.	167
6.	Reference List	169
7.	Appendix - I	188
8.	Appendix - II.....	191
9.	Appendix – III.....	199

LIST OF FIGURES

Figure 1: Fuel economy characteristics of a gasoline engine – Adopted from Reference [28].	14
Figure 2: Accessory power requirements of a full-size passenger car - Adopted from Reference [31].	15
Figure 3: Comparison of the increased rates of the fuel consumption with the A/C on and with the A/C off at different vehicle speeds - Adopted from reference [34]	17
Figure 4: The effect of vehicle axle ratio on fuel consumption and performance - Adopted from reference [51].	19
Figure 5: Tractive-power requirement to overcome the aerodynamic resistance and mechanical resistance versus the vehicular speed - Adopted from reference [69]. ...	21
Figure 6 : Effect of the reduction in aerodynamic resistance coefficient on the fuel economy at different speeds for a mid-sized passenger car - Adopted from reference [74].	23
Figure 7: Relationship between the number of stops and fuel consumption - Adopted from reference [110].	28
Figure 8: The representative driving cycle for the traffic corridor from Katubedda – Fort along the Galle Road for LDVs - Adopted from reference [159].	36
Figure 9: The representative driving cycle for Southern Expressway, Sri Lanka – Adopted from reference [162].	37
Figure 10: Driving cycle during morning peak hours at B130 route – Adopted from reference [163].	37
Figure 11: Driving cycle during noon peak hours at B130 route – Adopted from reference [163].	38
Figure 12: Driving cycle during evening peak hours at B130 route – Adopted from reference [163].	38
Figure 13: Driving cycle during peak hours at B128 route – Adopted from reference [163].	39

Figure 14 Driving cycle during off-peak hours at B128 route – Adopted from reference [163].	39
Figure 15: Worldwide harmonized Light duty vehicle Test Procedure (WLTP) - Adopted from reference [164].	41
Figure 16: ECE-R47 Driving Cycle - Adopted from reference [192].	50
Figure 17: a) Part 1 of WMTC b) Part 2 of WMTC c) Part 3 of WMTC - Adopted from reference [193].	50
Figure 18: Flowchart reflecting the overall research methodology.	61
Figure 19: Annotated Speed Comparison Graph of Two-laned Route Link Segments.	65
Figure 20: User Interface of the Geo-updater Application (when data collection frozen phase is shown on left and the active phase is shown on right).	67
Figure 21: Speed versus time plot for the collected set of data.	68
Figure 22 : Frequency plot showing the highest spectral component.	69
Figure 23: FFT transformed speed data sequence (Zoomed in).	70
Figure 24: Speed vs. Time graph when the data collection device is at rest.	71
Figure 25: Collected latitude and longitude data visualized on ArcGIS map.	72
Figure 26 : Portrayal of a Micro Trip.	73
Figure 27 : Spatial Data Mapping for the Collected Data (2W and 3W).	75
Figure 28: Spatial Data Mapping for the Collected Data (4W).	77
Figure 29 : Metabolic heat load distribution versus the body mass (kg) and the body height (m).	84
Figure 30: Metabolic heat load distribution versus body surface area (m^2) and the number of passengers. (Passenger units)	85
Figure 31 : Ambient heat load distribution versus average speed (m/s) and ambient temperature difference (K).	89
Figure 32 : Engine Load versus Engine RPM.	94
Figure 33: Operating regions of an alternator (Output Current, Efficiency vs Alternator RPM).	99
Figure 34: Flow chart for the process of fuel economy estimation.	110
Figure 35: Representative Urban Driving Cycle.	113
Figure 36 : Representative Extra-Urban Driving Cycle.	114

Figure 37 : Representative Driving Cycle.....	116
Figure 38 : Speed-Frequency Distribution of the Population data set.	118
Figure 39 : Speed-Frequency Distribution of the Representative Driving Cycle. ...	119
Figure 40 : Comparison of the Graphs for Acceleration-Frequency Distributions..	120
Figure 41 : Representative Urban Driving Cycle for 4W.	122
Figure 42 : Representative Extra Urban Driving Cycle for 4W.	122
Figure 43 : Representative Driving Cycle for 4W.	123
Figure 44 : Speed Frequency Distribution for the representative driving cycle.	124
Figure 45 : Speed Frequency Distribution for the population data set.	124
Figure 46: Speed vs Time (Step Input).	125
Figure 47 : Speed vs Time (Step Input).	128
Figure 48 : Engine Speed vs time (when step input is provided).	129
Figure 49: Mass fuel flowrate output (when step input is provided).	129
Figure 50: Speed vs Time (Ramp Input).	130
Figure 51: Engine Speed vs time (when ramp input is provided).	130
Figure 52 : Mass fuel flow rate output (when ramp input is provided).	131
Figure 53 : Input – Output representation of the developed theoretical model.	134
Figure 54: JP10 driving cycle data.	136
Figure 55: Engine speed profile when tested against JP10 driving cycle.	137
Figure 56 : Instantaneous Fuel Flowrate when tested against JP10 driving cycle..	137
Figure 57 : SC03 driving cycle data.	138
Figure 58: Engine speed profile when tested against SC03 driving cycle.	139
Figure 59 : Instantaneous Fuel Flowrate when tested against SC03 driving cycle..	139
Figure 60 : LA92 driving cycle data.	140
Figure 61 : Engine speed profile when tested against LA92 driving cycle.	141
Figure 62: Instantaneous Fuel Flowrate when tested against LA92 driving cycle. .	141
Figure 63: Colombo Metropolitan driving cycle data.	142
Figure 64: Engine speed profile when tested against Colombo Metropolitan driving cycle.	143
Figure 65: Instantaneous Fuel Flowrate when tested against Colombo Metropolitan driving cycle.	144
Figure 66 : WLTP driving cycle data.	145

Figure 67: Engine speed profile when tested against WLTP driving cycle.....	146
Figure 68 : Instantaneous Fuel Flowrate when tested against WLTP driving cycle.	146
Figure 69 : The relationship for average fuel economy between varying driving cycles versus WLTP.....	149
Figure 70 : New European Driving Cycle (NEDC) - Adopted from reference [159].	191
Figure 71: Federal Test Procedure (FTP)-72 driving cycle - Adopted from reference [159].	192
Figure 72: FTP-75 driving cycle - Adopted from reference [159].....	192
Figure 73: US06 Supplemental Federal Test Procedure (SFTP) driving cycle - Adopted from reference [159].	193
Figure 74: SC03 SFTP driving cycle - Adopted from reference [159].	193
Figure 75: Japanese (JP) 10-15 Mode driving cycle - Adopted from reference [159].	194
Figure 76: Common Artemis Driving Cycle (CADC) - Adopted from reference [159].	194

LIST OF TABLES

Table 1: Type ‘L’ Vehicle Categorization as per WMTC.	8
Table 2: Key Characteristics of Motorcycle Classes	8
Table 3: Classification of Light Duty Vehicles in Sri Lanka.....	9
Table 4: Energy Balance in terms of the percentage of fuel supplied [25].....	13
Table 5: Effect of engine accessories on the fuel economy of an intermediate car with automatic transmission [30].	16
Table 6: Components of aerodynamic resistance coefficient [69].....	22
Table 7: Corresponding fuel consumption and rolling resistance force for variable tyre inflation pressure values [96].....	25
Table 8: Commonly used Performance Values for cycle assessment [136].	34
Table 9: Performance Values of WLTP driving cycle [164].	41
Table 10: General Vehicle Categorization in the European Union [171].....	43
Table 11: 2W categorization adopted by the government of Sri Lanka (SL) for vehicle importation [184].....	45
Table 12: Motorcycle classification as per WMTC [185].	45
Table 13: Comparison of driving cycle tests to estimate emissions for various regions/countries. (Pre-Stage 2 -WMTC Period) [186], [187], [188], [189].	46
Table 14: Comparison of driving cycle tests to estimate emissions for various regions/countries. (Stage 2 -WMTC Period) [188], [189], [190], [191], [192].	47
Table 15: Comparison of driving cycle tests to estimate emissions for various regions/countries. (Post-Stage 2 -WMTC Period) [186], [187], [188], [189], [190], [191].	48
Table 16: Opted Routes for Data Collection in Colombo Metropolitan Area	63
Table 17: Classification of Speed Classes Classification	75
Table 18: Classification of Speed Classes. (4W)	77
Table 19: Metabolic load calculation of a passenger car. [216].	82
Table 20: Kinematic parameters for different driving cycles.	87

Table 21: Relative Humidity (RH) and Saturated Vapor Pressures at given temperature values.	96
Table 22: A/C load breakdown	98
Table 23: Summary of the engine auxiliary power demand	103
Table 24: Initialization of parameters for tractive power calculation	106
Table 25:BSFC Lookup Table	110
Table 26: Selection of Urban and Extra-Urban Representative Cycles using CSI scores of CPs.....	115
Table 27: CP values of the Representative Driving Cycle.....	116
Table 28: Selection of Urban and Extra-Urban Representative Cycles using CSI scores of CPs.....	121
Table 29: CP values of the representative driving cycle.....	123
Table 30: Comparison of CPs of the representative DC against regional DCs for 4W.	126
Table 31: Comparison of CPs of the representative DC against WMTC for 2W/3W.	127
Table 35: List of LDVs selected for the simulation study.	132
Table 36: Model output versus the simulated output	133
Table 37: Model tested performance against the manufacturers' data.	134
Table 38 : Comparison of average fuel economy values of different driving cycles.	147
Table 39 : Average fuel economy data for five different driving cycles.	148
Table 40 : Comparison of the Performance Values of different driving cycles [159].	194

LIST OF ABBREVIATIONS

Abbreviations	Definition
2W	Two-wheelers
3W	Three-wheelers
4W	Four-wheelers
AADT	Average Annual Daily Traffic
A/C	Air Conditioning
ADR	Australian Design Rules
ADT	Annual Daily Traffic
ADVISOR	ADvanced VehIcle SimulatOR
AFR	Air-Fuel Ratio
AMT	Automated Manual Transmission
AP	Afternoon Peak
API	Application Programming Interface
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
ASHRAE	American Society of Heating Refrigerating and Air-conditioning Engineers
AT	Automatic Transmission
BEV	Battery Electric Vehicle
BS	Bharat Standards
BSFC	Brake Specific Fuel Consumption
CADC	Common Artemis Driving Cycle
CAI	Controlled Autoignition
CC	Cylinder Capacity
CDA	Cylinder Deactivation
CDC	Colombo Driving Cycle
CI	Compression-Ignition
CMA	Colombo Metropolitan Area
CMDC	Colombo Metropolitan Driving Cycle

CP	Characteristic Parameter
CR	Compression Ratio
CSI	Cumulative Similarity Index
CUEDC	Composite Urban Emission Driving Cycle
CVT	Continuously Variable Transmission
DC	Driving Cycle
DSD	Divisional Secretariat Division
EOP	Evening Off Peak
EP	Evening Peak
EPA	Environmental Protection Agency
EPAS	Electronic Power Assisted Steering
EU	European Union
EV	Electric Vehicles
FC	Fuel Consumption
FT	Fixed Transmission
FTP	Federal Test Procedure
FWD	Front Wheel Drive
GFEI	Global Fuel Economy Initiative
GHG	Green House Gas
GIS	Geographic Information Software
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HEV	Hybrid Electric Vehicle
HPAS	Hydraulic Power Assisted Steering
HWFET	High Way Fuel Economy Test
IC	Internal Combustion
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMDC	Indian Motorcycle Driving Cycle
IMMA	International Motorcycle Manufacturers' Association
ISFC	Indicative Specific Fuel Consumption

ISO	International Standardization Organization
JP	Japanese Driving Cycle
LA01	Los Angeles 01 driving cycle
LA92	Los Angeles 92 driving cycle
LDV	Light Duty Vehicle
LoS	Level of Service
METI	Ministry of Economics, Trade and Industry
MOP	Morning Off Peak
MT	Manual Transmission
NEDC	New European Driving Cycle
NREL	National Renewable Energy Laboratory
OBD	On Board Diagnostic
PKE	Positive Kinetic Energy
PV	Performance Value
RH	Relative Humidity
RMS	Root Mean Square
RPM	Revolutions Per Minute
RWD	Rear Wheel Drive
SAE	Society of Automobile Engineers
SAFD	Speed Acceleration Frequency Distribution
SAPD	Speed Acceleration Probability Distribution
SC03	Supplemental Federal Test Procedure with A/C system turned on.
SDG	Sustainable Development Goals
SFC	Specific Fuel Consumption
SFTP	Supplemental Federal Test Procedure
SI	Spark Ignition
SL	Sri Lanka
SSD	Sum Square Difference
TPES	Total Primary Energy Supply
UNEP	United Nations Environmental Program
US	United States

US06	The United States Supplemental Federal Test Procedure
USCAFE	The United States Corporate Average Fuel Economy
USFTP	The United States Federal Test Procedure
WLTC	World Harmonized Light Vehicle Test Cycle
WLTP	World Harmonized Light Vehicle Test Procedure
WMTC	World Motorcycle Test Cycle