Impact of Intelligent Transportation Systems on Vehicle Fuel Consumption and Emission Modeling: An Overview

Article · January 2014

DOI: 10.4271/2013-01-9094

3 authors:

Waleed Faris
International Islamic University Malaysia

Hesham Rakha
Virginia Polytechnic Institute and State University

Salah A.M. Elmoselhy
Xiamen University of Technology

Vehicle fuel consumption and emission modelling: an in-depth literature review

Waleed F. Faris*

Department of Mechanical Engineering,
International Islamic University Malaysia,
Gombak, Kuala Lumpur, 53100, Malaysia
and
Center for Sustainable Mobility,
Virginia Tech Transportation Institute,
Virginia Polytechnic Institute and State University,
3500 Transportation Research Plaza, Blacksburg, VA 24061, USA
E-mail: wfaris@vt.edu
*Corresponding author

Hesham A. Rakha

Center for Sustainable Mobility,
Virginia Tech Transportation Institute,
Virginia Polytechnic Institute and State University,
3500 Transportation Research Plaza, Blacksburg, VA 24061, USA
E-mail: hrakha@vtti.vt.edu

Raed Ismail Kafafy, Moumen Idres and Salah Elmoselhy

Department of Mechanical Engineering,
International Islamic University Malaysia,
Gombak, Kuala Lumpur, 53100, Malaysia
E-mail: rkafafy@iium.edu.my
E-mail: midres@iium.edu.my
E-mail: salah.elmoselhy@msm.nl

Abstract: Modelling of vehicle fuel consumption and emissions has emerged as an effective tool to help develop and assess vehicle technologies and to help predict vehicle fuel consumption and emissions. A review to identify the current state-of-the-art on vehicle fuel consumption and emissions modelling is elucidated. This review categorises vehicle fuel consumption and emissions models into five classifications. The relevant main models to each of these classifications are presented. These models are then compared with regard to assumptions, limitations, merits, drawbacks, characteristic parameters, data collection techniques, accuracy, and relevance to road traffic. The study demonstrates that the trends of vehicle fuel consumption and emissions provided by current models generally do satisfactorily replicate field data trends. In addition, the paper demonstrates that mesoscopic models, empirical models, mean value-based models, and quasi dimensional models strike a balance between accuracy and simplicity and thus are very suitable for transportation and control applications. The study shows as well that no one model as yet fully meets the needs of transportation applications.

Keywords: engine and drive-train modelling; vehicle fuel consumption; vehicle emissions.

Reference to this paper should be made as follows: Faris, W.F., Rakha, H.A., Kafafy, R.I., Idres, M. and Elmoselhy, S. (2011) 'Vehicle fuel consumption and emission modelling: an in-depth literature review', *Int. J. Vehicle Systems Modelling and Testing*, Vol. 6, Nos. 3/4, pp.318–395.

Biographical notes: Waleed F. Faris is the Deputy Dean in the Office of Corporate Strategy and Quality Assurance at the International Islamic University Malaysia (IIUM), and also holds an appointment as an Associate Professor at the Mechanical Engineering Department and Mechatronics Department of the same university since 2004. He has been a Visiting Scholar in Virginia Tech Transportation Institute (VTTI), in 2008. He obtained his BSc in Mechanical Engineering with specialisation in Construction Equipment and Off-Road Vehicles from Zagazig University, Egypt, in 1989, MSc in Applied Mechanics from the same university, in 1996, and PhD in Non-linear Dynamics from Virginia Tech, USA, in 2003. He has to his credit three books and more than 100 technical papers in reputed journals and refereed conferences in vehicle dynamics and control and NVH. He is a member of the Japanese Society of Automotive Engineers, and a technical committee member and reviewer of several international journals and conferences worldwide.

Hesham A. Rakha is a Professor at the Charles E. Via Jr. Department of Civil and Environmental Engineering and the Director of the Center for Sustainable Mobility at the Virginia Tech Transportation Institute. He is a Professional Engineer in Ontario and a member of the Institute of Transportation Engineers (ITE), American Society of Civil Engineers (ASCE), Institute of Electrical and Electronics Engineers (IEEE), and Transportation Research Board (TRB). He is on the Editorial Board of the *Journal of Transportation Letters* and an Associate Editor for the *IEEE Transactions of ITS* and the *Journal of ITS*. He has authored/co-authored a total of 200 refereed publications in journals and conference in the areas of traffic flow theory, traffic modelling and simulation, dynamic traffic assignment, traffic control, transportation energy and environmental modelling, and transportation safety modelling.

Raed Ismail Kafafy is an Assistant Professor at the International Islamic University Malaysia (IIUM). He received his BSc and MSc from Cairo University, Egypt. In addition, he received his PhD from Virginia Polytechnic Institute and State University, USA. His research area includes advanced space propulsion, computational engineering, plasma and gas physics, and space systems.

Moumen Idres is an Assistant Professor at the International Islamic University Malaysia (IIUM). He received his BSc and MSc from Cairo University, Egypt. In addition, he received his PhD from Old Dominion University, USA. His research area includes aerospace propulsion, acoustics and noise analysis, computational fluid mechanics, flight mechanics and control, and renewable energy.

Salah Elmoselhy is a PhD student working with the Department of Mechanical Engineering at the International Islamic University Malaysia (IIUM) and with the Center for Sustainable Mobility at Virginia Polytechnic Institute and State University (Virginia Tech).

1 Introduction

The transportation sector is the third largest consumer of energy and the largest consumer of petroleum products and is one of the greatest contributors to air pollution worldwide (United Nations Economic and Social Council, 2009). Emissions from vehicles contribute to smog, low visibility, and various greenhouse gas (GHG) emissions. About half of all air pollution and more than 80% of air pollution in cities are produced by the transportation sector worldwide (United Nations Economic and Social Council, 2009). Its energy consumption is growing faster than that of other sectors, driven by the rapid increase in motorisation and strong transport demands from economic development. Meanwhile, the transport sector is the primary source or precursor of air pollution and the second largest contributor to carbon dioxide emissions (United Nations Economic and Social Council, 2009). These facts require the transport sector to take more effective mitigation and adaptation measures to reduce energy consumption and emissions. Therefore, automobile manufacturers are currently under pressure to produce more environmentally friendly vehicles (United Nations Economic and Social Council, 2009).

Vehicle fuel consumption and emission models are currently the primary tools for evaluating the regional impacts of transportation projects and in evaluating developed transportation technologies. In typical applications, a transportation planning model such as TRANPLAN (The Urban Analysis Group, 1992), MINUTP (The Seider Group, 1997), or EMME/2 (INRO Consultants, 1996) is first used to determine the average speed and total vehicle-miles of travel for the network or facility being considered. Then, a fuel consumption and emissions model such as MOBILE6 (United States Environmental Protection Agency EPA, 1994), EMFAC [California Air Resources Board (CARB), 1991], or motor vehicle emission simulator (MOVES) (Chamberlin et al., 2011) is used to compute the average fuel consumption and emissions rates for the facility. Within this step, a base emissions rate reflecting fuel consumption and emissions measurements that were gathered in a laboratory using pre-defined test drive cycles is first selected for the facility considered. This base rate is then modified to account for differences in average speeds between the laboratory and real world cycles, as well as for differences in temperature, vehicle load, fleet composition, accrued mileage of vehicles within the fleet, type of fuel used, and vehicle operating conditions. Total fuel consumption and emissions are finally obtained by multiplying the resulting rates by the estimated vehicle miles travelled on the facility (Yue, 2008).

Macroscopically, single fuel consumption and emissions rates are produced for each average speed input. These rates are produced under the assumptions that all vehicles pollute similarly for the same average speed and vehicle-miles travelled and that variations in driver behaviour can be neglected (An et al., 1997). This raises an issue when the drive cycles encountered in the field differ from those assumed within the models, since estimated emission rates may not correspond to actual emissions. A particular problem occurs when comparing drive cycles with identical average speeds, as identical emission rates would then be estimated for all cycles despite differences in the second-by-second speed profiles. This research reviews the current state-of-the-art on vehicle fuel consumption and emissions modelling and the models that address these issues. It classifies vehicle fuel consumption and emissions modelling into five classifications and presents the relevant models to each of them. These models are then compared with regard to assumptions, limitations, merits, drawbacks, characteristic parameters, data collection technique, accuracy, relevance to road traffic, and validation.

A discussion section then follows on these models and comparisons highlighting the key challenges. The conclusion section then elucidates the key future research directions in this research area.

2 Vehicle fuel consumption and emissions modelling

Many approaches have been developed to model vehicle fuel consumption and emission rates in order to estimate vehicle fuel consumption and emission rates. They can be classified into five categories of classification:

1. scale of the input variables-based modelling
2. formulation approach-based modelling
3. type of explanatory variable-based modelling
4. state variable value-based modelling
5. number of dimensions-based modelling.

Based on the scale of the input variables the current state-of-the-art and current state-of-practice models can be divided into three categories: microscopic, mesoscopic, and macroscopic models. The subcategories of the formulation approach-based modelling classification, i.e., the way of building model-based modelling classification, are analytical, empirical, statistical, and graphical models. In the explanatory variable-based modelling classification, there are three subcategories: average speed, instantaneous speed, and specific power models. The state variable value-based modelling classification can be divided into crank-angle resolution-based models and mean value-based models. The subcategories of the number of dimensions-based modelling classification are zero/one dimensional/single zone, quasi dimensional, and multi-dimensional/multi-zone modelling. These five classifications will be investigated in the following subsections.

2.1 Scale of the input variables-based modelling

Let us start with investigating the scale of the input variables-based modelling classification that is divided into: microscopic models, mesoscopic models, and macroscopic models, as suggested by Yue (2008). Microscopic models use instantaneous speed and acceleration data to estimate vehicle fuel consumption and emission rates. The fuel consumption and emission estimates from microscopic models are instantaneous rates as well. Macroscopic models use aggregate network-based parameters to estimate network-wide fuel consumption and emissions rates. Mesoscopic models use scales that lie in-between the macroscopic scale and microscopic scale, such as link-based estimates (Yue, 2008). All of these three categories can be called modal models if they account for different standard operating modes.

2.1.1 Microscopic models

Microscopic models estimate instantaneous vehicle fuel consumption and emission rates that are then aggregated to estimate network-wide measures of effectiveness. Instantaneous fuel consumption models are derived from a relationship between fuel consumption rates and instantaneous vehicle power. Second-by-second vehicle characteristics and road conditions are required in order to estimate fuel consumption in these models. Due to the disaggregate characteristics of the fuel consumption data, these models are usually used to evaluate individual transportation projects. Instantaneous fuel consumption models can be used in microscopic traffic simulation packages to estimate fuel consumption based on instantaneous speeds and accelerations of individual vehicles (Yue, 2008). The key microscopic models include:

1 comprehensive modal emission model (CMEM)
2 VT-microscopic model
3 vehicle transient emissions simulation software (VeTESS)
4 NetSim
5 VERSIT
6 passenger car and heavy duty emissions model (PHEM)
7 EMIT
8 MOVES
9 vehicle dynamics models.

These microscopic models will be highlighted in this subsection.

An et al. (1997) developed a modal emissions model, called CMEM, which is based on a simple parameterised empirical approach and consists of six modules that predict engine power, engine speed, air/fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction. This model was built based on an in-house dynamometer test on 300 real world vehicles. Three dynamic variables (acceleration, air/fuel equivalence ratio, and fuel rate), second-by-second speed, road grade angle, and accessory use (such as air conditioning) are used as the input operating variables. The instantaneous emission as the key output was modelled as the product of three components: fuel rate, mass of engine-out emissions per grams of fuel consumed, and catalyst pass fraction which is the ratio of tailpipe emission to engine-out emission, as shown in equation (1), (Yue, 2008).

$$tailpipe\ emissions = FR.\left(\frac{g_{emission}}{g_{fuel}}\right).CPF \tag{1}$$

As to the first of the six modules of which this model is composed which is the engine power demand module, the engine power output is calculated using equations (2).

$$\begin{aligned} P_{tract} &= A.v + B.v^2 + C.v^3 + M.a + M.g.v.\sin\theta \\ P &= \frac{P_{tract}}{\eta_{tf}} + P_{acc} \end{aligned} \tag{2}$$

For the engine speed module, engine speed is simply presented in terms of vehicle speed using gear ratios and a shift schedule to determine up- or downshift. In the air/fuel ratio module, the air/fuel ratio can be the typical air/fuel ratio in one of three regions: lean, stoichiometric, and rich. As to the fuel rate module, the fuel rate is evaluated using equation (3).

$$FR \approx \phi \left(kNV + \frac{P}{\eta} \right) \frac{1}{44} \tag{3}$$

For the engine-out emissions module, the engine-out emissions is evaluated using equations (4).

$$\begin{aligned} &ECO \approx \left[C_O \left(1 - \Phi^{-1} \right) + a_{CO} \right] FR \\ &EHC \approx a_{HC} FR + r_{HC} \\ &ENO_x = a_{1NOx} \left(FR - FR_{NOx} \right), \quad \Phi < 1.05 \\ &ENO_x = a_{2NOx} \left(FR - FR_{NOx} \right), \quad \Phi \geq 1.05 \end{aligned} \tag{4}$$

As to the catalyst pass fraction module, the catalyst pass fraction is evaluated using equation (5).

$$CPF(ei) = 1 - \varepsilon_{ei} * \exp\left\{ \left[-b_{ei} - c_{ei} * \left(1 - \Phi^{-1} \right) \right] * FR \right\} \tag{5}$$

The CMEM is capable of doing the following:

a estimating the second-by-second emissions based on network changes that affect the acceleration/deceleration of vehicles in traffic

b estimating the total vehicular emissions (TVE) for the whole simulation period for each pollutant from a congested road network.

The main limitations of CMEM include:

1 it does not represent real world driving conditions as data were collected using a dynamometer

2 it is unable to estimate emissions from heavy duty vehicles such as trucks and buses

3 it is incapable of estimating particulate emissions.

Despite these limitations, it is still among the best modal emissions models (Noland and Quddus, 2006).

The CMEM is adopted by PARAMICS microscopic simulator, which was originally developed at the Edinburgh Parallel Computing Center in Scotland, provides the most comprehensive visual display for viewing the results through multiple windows, and animation of vehicle movements including three-dimensional (3D) displays during the simulation run. Although the model needs more calibration and validation, its applications, such as simulation of congested traffic networks at the level of individual vehicles, in Britain seem promising. PARAMICS can be applied to integrated networks and has potential applications in traffic management and control, traffic control centre modelling, and personal access to predictive travel information. It is scalable and includes a sophisticated microscopic car-following and lane changing model for roads up to 32 lanes in width. In addition, PARAMICS enables the modelling of the interface between drivers and intelligent transportation systems (ITSs). It provides integrated modelling of networks consisting of freeways, arterials, and minor roads, various intersection types (signals, stop signs, and roundabouts) and parking garages with no limit on the network size, and the number of vehicles that can be simulated. PARAMICS is widely used in Europe in transportation applications, uses credible theories, and has the ability to output measures of performance such as travel times and speeds. PARAMICS limitations include:

1 lack of equilibrium traffic assignment

2 limited options in modelling traveller information/guidance, which means that the model updates the routing instructions at each intersection instead of being path based, which may result in myopic travel paths with extensive twists and turns

3 not being able to explicitly model a number of control options such as bus signal preemption from mixed-lanes

4 limited user options in modelling incidents and work zones (Boxill and Yu, 2000).

Rakha and Ahn developed a microscopic vehicle fuel consumption and emission model called VT-Micro that predicts the instantaneous fuel consumption and emission rates of HC, CO, NOx and CO_2 of individual vehicles based on their instantaneous speed and acceleration levels (Ahn and Trani, 1999; Rakha and Van Aerde, 2000; Ahn, 2002). This model is intent to show how significant the impact of the speed and acceleration variation is on vehicle fuel consumption and emission rates. The inputs to the VT-Micro are the instantaneous speed and acceleration and the outputs are instantaneous fuel consumption and emission rates of individual vehicles (Yue, 2008). Equation (6) describes the general mathematical formulation of the VT-Micro model to predict the instantaneous fuel consumption and emission rates of individual vehicles (Yue, 2008).

$$\begin{aligned} MOE_e &= \sum_{i=0}^{3}\sum_{j=0}^{3}\exp\left(k_{i,j}^{e} * v_{VT}^{i} * a^{j}\right), \quad \text{for } a \geq 0 \\ MOE_e &= \sum_{i=0}^{3}\sum_{j=0}^{3}\exp\left(l_{i,j}^{e} * v_{VT}^{i} * a^{j}\right), \quad \text{for } a < 0 \end{aligned} \tag{6}$$

The model accounts for the accelerating, idling, cruising and decelerating driving modes. This split is implemented in the VT-Micro to account for differences in emission rate sensitivity to speed between acceleration and deceleration modes of operation of vehicles. Another important feature is the use of natural logarithms to ensure that non-negative fuel consumption and emission rates are produced by the models. The VT-Micro model has been evaluated against field data of the eight ORNL test vehicles (Ahn, 2004). The study shows that VT-Micro is able to follow closely the trends in increasing fuel consumption with higher speeds and sharper acceleration. The VT-Micro model provides good fit in terms of the absolute values of vehicle fuel consumption and emission rates. The model estimates vehicle fuel consumption to within 2.5% of actual measured field values. The VT-Micro model has been incorporated within INTEGRATION, a microscopic traffic simulation package, to further demonstrate its application to traffic engineering, such as evaluating transportation network improvements (Yue, 2008). INTEGRATION appears to have the highest probability of success in real world transportation applications (Tapani, 2005). Although the VT-Micro model seems to be the leading model in predicting instantaneous fuel consumption and emission rates, it is based on empirical formulae and thus provides unexplainable mathematical trends.

VeTESS is another microscopic emission model but it adopts a quasi steady state modelling approach by taking into account the dynamic behaviour of the engine. The input into the model is driving pattern, gradient, and vehicle specifications. The model output is the engine power and emission rate. The emission components in this model are NOx, COx, HC, and PM. VeTESS evaluates the engine operating conditions from the total force acting on the vehicle through equation (7).

$$F_{total} = F_{accel} + F_{grad} + F_{roll} + F_{aero} \tag{7}$$

Thus, VeTESS then evaluates the engine speed and engine torque from the forces acting on the vehicle and references after that the corresponding values for the emission components using emission maps. The VeTESS estimates for fuel consumption and emissions have generally an accuracy within 10% to 20%. The main limitation of VeTESS is that it considers only one vehicle at a time and one journey at a time.

VeTESS is adopted by CORSIM software. CORSIM was developed by the Federal Highway Administration (FHWA) is the first windows based version of a traffic simulation model (US Department of Transportation, 1996). It is a microscopic stochastic traffic simulation model that can realistically represent the real world dynamic traffic environment. It can be applied to integrated networks and can model four different types of on-ramp freeway metering (clock-time, demand/capacity, speed control and gap acceptance merge control). CORSIM has the most sophisticated car-following and lane-changing logic to simulate vehicle movements on a second-by-second basis. It adopts NETSIM model for adjoining surface streets to represent the real world dynamic traffic environment. CORSIM has recently been released as a commercial product by the FHWA. The model is obtainable by the public and can be used to simulate freeway and arterial intersection designs to assess a set of transportation control options offline. Although the model uses credible theories and has the ability to produce measures of performance such as travel times and speeds, the model is not tested as well as VT-Micro (Boxill and Yu, 2000). CORSIM appears to have the second highest probability of success in real world applications next to INTEGRATION (Tapani, 2005).

The VERSIT+^{micro} was developed in the Netherlands by TNO to simulate the traffic emissions of CO_2, NOx and PM_{10} as well as energy use factors as outputs on the basis of the instantaneous velocity and acceleration of a vehicle as inputs. The emission factors (EMFACs) for this model are differentiated for various vehicle types and traffic situations, and take into account real world driving conditions. VERSIT+ is unique in that it yields consistent results on national, regional and local scales placing it at bar with the INTEGRATION model. It can be used for investigating national GHG reduction strategies but also for local air quality improvement. It can be used as well for environmental monitoring as well as for assessment of environmental effects of traffic measures. Using advanced statistical modelling techniques, VERSIT+ finds the best fitting EMFAC equation for any given driving pattern and thus makes emission prediction for road traffic (trucks, buses, passenger cars and motorcycles) helping decision-makers to make well-informed vehicle technology incentives. VERSIT+ can be directly linked to traffic simulation models allowing for direct evaluation of impact of traffic measures (such as green wave, or trajectory control) on the air quality. The key drawback of the VERSIT+ is the linear dependence of the emission estimates on the velocity of the vehicle which limits the effect of the velocity on the emission estimates (Smit et al., 2007).

The VERSIT+^{micro} is adopted by Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks (AIMSUN) software. As an efficient traffic simulator to simulate urban and interurban traffic networks containing a wide range of ITS applications, AIMSUN emerged to provide the user with a user friendly interface to facilitate both the model building and the use of simulation as an assessment tool. It was developed by the Polytechnic University of Catalunya in Barcelona providing detailed statistical output, such as flows, speeds, and travel times, in terms of printouts or plots, for time-dependant origin-destination matrices. The strengths of this model lie in the following: user friendly interface, the ability to deal with different traffic networks, and the ability to model different types of traffic control. Its weakness is that the information or signalisation to implement route guidance must come from an external system. By making more calibration and validation, AIMSUN can be brought to the forefront of micro-simulators to be at bar to a large extent with Corridor microscopic simulation (CORSIM) (Boxill and Yu, 2000).

The PHEM uses an emissions map as a look-up table to estimate emissions microscopically. The emission map is developed in terms of the engine operating parameters (e.g., engine speed and torque), rather than the aggregate vehicle parameters (e.g., vehicle speed and kinematic power). The PHEM model was first developed for use in predicting the emissions of heavy duty vehicles but has recently been extended to passenger cars. The inputs to the model are road speed and load and the output is instantaneous emission estimates for CO, CO_2, HC and NOx. PHEM cannot as yet model microscopically PM emissions and there are not yet quantitative validation data available for this model. The model provides predictions of aggregate emissions that are less accurate than the predictions of the INTEGRATION model (Zallinger et al., 2005; North, 2006).

The PHEM is adopted in the VISSIM software. VISSIM is another microscopic simulator that can be applied to integrated networks. It is a time step and behaviour based simulator used for transit signal priority and intersection/interchange design and operations. VISSIM can analyse traffic and transit operations with no limit of network size and under constraints, such as lane configuration, traffic composition, traffic signals, block signals, transit stops, variable message signs, etc., making it thus a useful tool for the evaluation of various alternatives. The input to the model is time-dependant origin-destination matrices whereas it generates numerous user-customisable output files such as detailed travel time and delay statistics, queue length statistics, detailed signal timing information (green time, cycle length, etc.), protocol of detector actuations and transit priority calls, graphical output such as time space diagrams and speed profiles, and environmental indicators (Boxill and Yu, 2000). Not only is not it as good as PARAMICS in terms of being tested for real world applications and of being obtainable by the public, but also it requires a significant amount of time to code the input data and it does not include assignment algorithms.

EMIT model is another vehicle emissions model that evaluates emissions depending on vehicle speed and acceleration, taking into account vehicle characteristics such as total mass, engine, and installed catalytic converter. The key emission component in this model is CO_2. The model input includes the speed, acceleration, and mass of vehicle as well as the road grade angle. EMIT has been validated and has been used successfully to evaluate the environmental impact of intervehicle communication (IVC) technologies (Sommer et al., 2011).

MOVES is an emission model and simulator that was developed by the United States Environmental Protection Agency (EPA) and is currently adopted officially in the USA for vehicle fuel consumption and emission rates evaluation. The current version of

MOVES is MOVES2010. The input into this model is the vehicle's instantaneous speed and acceleration and the output of this model is the rate of emission components that include NOx, PM, CO, CO_2, SO_2, and NH_3. The MOVES model employs a modal emission rate approach relying on second-by-second data to develop emission rates. MOVES software incorporates a graphical user interface. It uses a relational database to store underlying data, and the calculation of aggregate energy and emission inventories rather than only calculating per-mile EMFACs (Boulter et al., 2007). Albeit its good estimation of vehicle's fuel consumption and emission rates, MOVES model is relatively time-consuming.

In order to evaluate vehicle's instantaneous acceleration, one may consider a vehicle kinematics model, a constant power vehicle dynamics model, a variable power vehicle dynamics model, or a more sophisticated gear-shifting model. The vehicle kinematics model developed by Rakha et al. (1999) estimates maximum vehicle acceleration based on vehicle's tractive effort and aerodynamics, rolling resistance forces, and grade resistance forces. That vehicle kinematics model has proved to be more accurate than the similar vehicle dynamics model for estimating maximum vehicle acceleration levels proposed by Archilla, and De Cieza (1999). That model has helped in redrawing realistically the curves for predicting vehicle speeds as a function of the distance travelled and of the percentage grade along the section. Although that model is not sophisticated, its accuracy is not high. The constant power vehicle dynamics model estimates maximum vehicle acceleration levels based on vehicle's tractive effort. Though its formulation is simpler than the vehicle kinematics model, its accuracy is not high as well. The variable power vehicle dynamics model introduced the concept of linearly increasing vehicle variable power to the basic vehicle dynamics model of 'constant power vehicle dynamics'. Yet, the accuracy of that model is not high as well. A vehicle dynamics or gear-shifting modelling approach is better because the model parameters can be adjusted to reflect different weather, tyre, and roadway surface conditions without the need for gathering any field data. Apart from the INTEGRATION software (which uses a vehicle dynamics model), state-of-practice microscopic traffic simulation software, such as Paramics, VISSIM, AIMSUN, and CORSIM, use kinematic acceleration-speed relationships to model vehicle accelerations. Research is currently needed to characterise analytically the relationships, if any, between the driver's throttle input and the vehicle conditions, roadway conditions, and surrounding traffic conditions (Rakha et al., 2010).

2.1.2 Macroscopic models

Macroscopic models use average aggregate network parameters to estimate network-wide energy consumption and emission rates. The key models in the macroscopic vehicle fuel consumption and emissions modelling subcategory include:

1 MOBILE
2 EMFAC
3 CORFLO
4 Watson model
5 COPERT.

The following subsections will elucidate these macroscopic models.

The MOBILE source EMFAC model is a vehicle emission model and model-based transportation macro-simulation software that has been commonly utilised and officially adopted in the USA for transportation planning and conformity analysis in the USA, which is the largest country in energy consumption. The MOBILE model was developed by the US EPA, and the current version of MOBILE model is MOBILE6.2. The MOBILE model estimates are a function of the vehicle's average speed, vehicle's technology, vehicle's age, ambient temperature, fuel parameters, and vehicle's operating mode [National Research Council (NRC), 1995]. Eight pollutants can be estimated by MOBILE6 model: HC, CO, NOx, CO_2, PM, SO_2, NH_3, and six hazardous air pollutants (HAP). The CO_2 emission estimate from MOBILE6 is unlike other MOBILE6 emission estimates. This CO_2 emission rate estimate is based on vehicle type only and is not affected by speed, temperature, and gasoline type. In this model, basic emission rates are derived from emissions tests conducted under standard conditions such as temperature, fuel, and driving cycle. Speed correction factor (SCF) is then used when vehicle average travel speed is different from the average travel speed derived from the standard testing drive cycle. The SCF is derived based on emission rates from a specific number of testing driving cycles (Yue, 2008). Yet, MOBILE6 cannot estimate fuel consumption and thus has been officially replaced by MOVES2010 model in the USA.

The EMFACs model is another vehicle emission model that has been widely used. It was developed by California Air Resources Board (CARB) and is used only in the state of California in the USA, while MOBILE model is used in all other states in the USA. The current version of EMFAC model is EMFAC2007. The EMFAC emission rate estimates are as well a function of vehicle average speed. The EMFAC2007 can be used to estimate HC, CO, NOx, CO_2, PM, SOx, pb, and fuel consumption. Adjustments are used in this model for different temperatures, gasoline types, humidity, etc., after evaluating the basic emission rates that are derived from emissions tests conducted under standard conditions. Albeit the EMFAC model is good for estimating emission rates, it ignores the impact of ITSs strategies, such as traffic signal coordination, and therefore has been officially replaced by MOVES2010 model in the USA.

The MOVES model is adopted in the transportation analysis and simulation system (TRANSIMS) software that was developed at the Los Alamos National Laboratory, in Los Alamos, New Mexico. TRANSIMS is based on simple car-following and lane changing logic as well as on cellular automaton technique. It creates a virtual metropolitan region with a complete representation of the region's individuals, their activities, and the transportation infrastructure. It simulates the movement of vehicles across the transportation network on a second-by-second basis and can estimate vehicle emissions and judge the overall performance of a transportation network. However, TRANSIMS is unobtainable by the public.

CORFLO is a macroscopic traffic model and traffic simulation software that was developed by the Federal Highway Administration, USA. CORFLO's macroscopic modelling approach allows for fast simulation times and analysis of design control scenarios. It is designed for integrated traffic network evaluation and is a well calibrated and documented macroscopic model. The model is based on the conservation equation and a dynamic speed density equation. Although it can run on inexpensive computers, CORFLO lacks the capability to simulate most ITS applications and does not account for dynamic rout guidance modelling (Boxill and Yu, 2000).

Watson and Milkins (1980) used average speed to develop a fuel consumption model. The model incorporates the changes in the positive kinetic energy during acceleration as a predictor variable as shown in equation (8).

$$F = K_1 + K_2 / V_S + K_3 V_S + K_4 PKE \tag{8}$$

The term PKE represents the sum of the positive kinetic energy changes during acceleration in m/s^2, and is evaluated using equation (9).

$$PKE = \sum \left(V_f^2 - V_i^2 \right) / \left(12.960 X_S \right) \tag{9}$$

When the average speeds are high enough, the aerodynamic effects on fuel consumption become significant. This usually occurs at average speeds over 55 km/h (Evans and Herman, 1976). The model helps in showing that it is easier to achieve steady state speed requirement under highway driving conditions. The model inputs are average speed, final speed, initial speed, and total section length. The model output is fuel consumption. Although Watson model is good for estimating fuel consumed, the accuracy of its estimation is less than that of instantaneous speed-based models.

The computer programme to compute emissions from road transport (COPERT) is an average speed based macroscopic emission model that was developed by the European Environment Agency and is widely adopted in transportation applications in Europe (Lei et al., 2010). The input into this model is the vehicle's average speed and the output of the model is the emission rate. The model was developed based upon the principle that the average EMFAC for a certain pollutant and a given type of vehicle varies according to the average speed during a trip. COPERT is intent to be used for emission inventories and dispersion modelling applications (Boulter et al., 2007). However, in modelling the emission rates of heavy duty vehicles, COPERT model is inherently unreliable at speeds above 100 km h^{-1} (Panis et al., 2007).

2.1.3 Mesoscopic models

The input variables to mesoscopic model are more disaggregate than macroscopic model and more aggregate than microscopic model. Generally, mesoscopic models use a few explanatory variables to estimate vehicle fuel consumption and emissions (Yue, 2008). The key models in the mesoscopic vehicle fuel consumption and emissions modelling subcategory include:

1 elemental model

2 CONTRAM

3 mobile emission assessment system for urban and regional evaluation (MEASURE) model.

The elemental model, which is based on average speed, was proposed by Herman (Chang and Evans, 1981; Evans and Herman, 1978). It is a simple theoretically-based model expressing fuel consumption in urban conditions as a linear function of the average trip time per unit distance, i.e., reciprocal of average speed. This model is presented in equation (10).

$$\Phi_E = K_1 + K_2 T, \quad \text{for } v < 55 \text{ km/hr} \tag{10}$$

In average speed models, fuel consumption rates as the model output are a function of trip time, trip distance, and average speed as the model inputs. Since these models do not adequately take into account aerodynamic drag resistance at high speeds, they should only be used for average speeds of less than 55 km/h in most cases (Akcelik, 1985). The elemental model is adopted in the SIDRA INTERSECTION software that was developed by Akcelik (Akcelik, 1985; Richardson and Akcelik, 1981) and that is widely used in transportation applications in Australia. This software helps in separately estimating fuel consumption in each of the three portions of an urban driving cycle, namely, during cruising, idling, and deceleration-acceleration cycle. The analysis of vehicle fuel consumption and emission rates based on modelling indicated that vehicle fuel consumption and emission rates increase considerably as the number of vehicle stops increase especially at high cruise speed (Ding, 2000). The main drawback of this model is that it does not capture transient changes in vehicle's speed and acceleration.

The continuous traffic assignment model (CONTRAM) is a mesoscopic model and simulator that is concerned with the dynamics of the flow of heavy traffic using aggregated speed-density functions to model the behaviour of that flow (Sommer et al., 2011). CONTRAM was developed by TRL and Mott McDonald and is intent to model integrated traffic links with complex travel behaviour, with time varying network conditions, and with the effects of ITS measures, such as route guidance. The core of CONTRAM is a dynamic assignment model that predicts traffic routes, link flows and queues and delays at intersections as they evolve over time. Therefore, CONTRAM is capable of accurately representing time varying network conditions. Though CONTRAM model deal with multiple classes of vehicles, it lacks the ability to output measures of performance such as travel times and speeds nor does it seem to be able to model most of the relevant ITS functions, e.g., it lacks the capability to model incidents or driver information systems (Boxill and Yu, 2000).

The MEASURE was developed by researchers at The Georgia Institute of Technology. The MEASURE model is a geographic information system GIS-based modal emissions model process that predicts modal vehicle operations and generates mesoscopic estimates of HC, CO, and NOx emissions (Bachman and Sarasua, 1996, 2000). This model includes two major modules: start emission module and on-road emission module. Emission rates are modelled based on a refined tree-based regression analysis of vehicle emission test data from the US EPA and CARB. Emission rates are a function of vehicle model year, vehicle fuel delivery technology, high or normal emitter vehicle, and modal variables. For the start emission module, the vehicle registration data are used to get vehicle cold and hot-start characteristics distribution. The start emission estimates are evaluated based on the start characteristics distribution and start emission rates. The on-road emission module estimates vehicle emission based on different operating modes: idle, cruise, acceleration, and deceleration. These modes are constructed based on average travel speed, roadway characteristics, traffic flow, and volume to capacity ratio. The MEASURE model is compatible with most of the traditional microscopic traffic simulation packages and models. Outputs from microscopic traffic simulation package or travel demand forecasting models along with roadway conditions, traffic control conditions, traffic conditions, and facility type are used as the input into the regression analysis to calibrate the model. The vehicle activity data, fleet composition characteristics, and operating conditions are then used as inputs into the model to get emission estimates (Yue, 2008).

2.2 Formulation approach-based modelling

Based on the formulation approach-based modelling, i.e., the way of building the vehicle model, the current-state-of-the-art and current state-of-practice models can be divided into four categories: analytical, empirical, statistical, and graphical modelling. The analytical modelling of a vehicle models the vehicle in terms of mathematical formulae which describe the relationships between the vehicle subsystems based entirely on the principles of physics. Empirical modelling is an approach that uses observations and the trial-and-error method to model a system. Statistical modelling is an approach that solely uses data and statistical methodologies to model a system. Graphical modelling is an approach that uses graphical tools and graphical methods to model the subsystems of a system as unified objects connected with each other. These subcategories of the second classification of models will be presented in this section.

2.2.1 Analytical models

Analytical modelling has been adopted in numerous research papers in order to model vehicle powertrains. For example, Lavoie and Blumberg (1980) proposed a thermodynamics-based model to predict fuel consumption, and emissions as a function of engine design parameters and operating conditions. Albeit the validation of that model proved its reliability in predicting fuel consumption, it is valid only for spark ignition (SI) engines.

Metallidis and Natsiavas (2003) proposed non-linear models of the dynamics of single- and multi-cylinder reciprocating engines, which may involve torsional flexibility in the crankshaft. These models took into account the torsional flexibility in the crankshaft and the dependence of the engine moment of inertia on the crankshaft rotation. A linearised version of the models was presented to acquire insight into some aspects of the system dynamics such as determining the steady state response and investigating the effect of engine misfire on fuel consumption and emission rates. Yet, these models are relatively of intensive computational time.

Harris and Pearce (1990) developed a mathematical model of the performance of a governed diesel engine using the following concept. At any throttle setting, and as torque is increased, the speed of a diesel engine will decrease from its value at zero torque and if torque increases further, the engine then operates along the locus of these points where the fuel delivery is a maximum. That model is simple enough to model and to indirectly measure tractor engine performance. Albeit it helps in evaluating the fuel consumption rate of tractor engines, the model does not account for estimating the emission rates of tractor engines.

Khayyam et al. (2008) developed an analytical model of fuel consumption (AMFC) to coordinate the driving power and to manage the overall fuel consumption for an internal combustion engine vehicle. Their model effectively evaluates the different loads applied on the vehicle including road-slope, road-friction, wind-drag, accessories, and mechanical losses. However, the model is relatively calculation intensive.

Zargari and Khan (2003) presented a model for the estimation of fuel consumption for bus operation on transitways/busways serving major travel corridors. That bus fuel consumption model is reported for standard and articulated buses. Yet, that model lacks simplicity and cannot be easily integrated into modern automobile control systems without simplification which in turn may lead to modelling errors.

Oberg (2001) extended previously developed analytical models for four cylinder turbocharged diesel engine that has no throttling developed by Karlsson (2001) and by Nyberg and Sutte (2004). In addition, Oberg presented the diesel engine combustion model and exhaust model developed by Butschek (2000). Oberg made extensions to the pumping and turbo sub-models of these already developed diesel engines models and developed a model for both exhaust gas recirculation (EGR) and variable nozzle turbine (VNT) turbocharger of the diesel engine. Albeit these models give insight into what influence the rate of fuel consumption, Oberg reported that the EGR, and the VNT are difficult to be analytically modelled satisfactorily.

Hillion et al. (2008) proposed a model-based control strategy to adapt the fuel injection settings according to the intake manifold condition on a diesel homogenous charge compression ignition (HCCI) engine. For that purpose, the start of injection is adjusted based on the knock integral model (KIM) and intake manifold condition. The KIM, originally developed by Livengood and Wu (1955), is a seminal and widely used model that gives an implicit relation between the start of injection crankshaft angle, start of combustion crankshaft angle, and the physical in-cylinder parameters such as cylinder pressure, cylinder temperature, in-cylinder burned gas rate, and the fuel/air ratio.

Kulkarni et al. (1992) reported that a turbo charged diesel engine without any governor or controller of fuel pump is normally represented by a fourth order model. They used model order reduction technique originally developed by Anderson (1979), by separating the dynamics into fast and slow modes and assuming that the fast modes settle quickly. The reduced order model was validated through simulation using typical data. They concluded that a simplified model, obtained by neglecting the manifold volumes, would give erroneous results.

Yang and Sorenson (1992) developed a physical model for the diesel fuel injection electronic unit injector and the electronic distributor pump system. The model incorporates a simplified characteristic line method for determining the hydraulic transients in high pressure fuel lines and a transmission line analogy method for modelling magnetic processes in the solenoid. Yet, it is relatively calculation intensive.

Xia and Oh (1999) developed a physical dynamic torque converter model to reduce fuel consumption. This model satisfies the energy conservation law and dynamic torque balance for all converter elements. The model was validated successfully and the results showed that converter dynamics have a significant effect on vehicle launch performance and thus on fuel economy. However, the model needs to be simplified in order to be easily integrated into vehicle control applications.

Wu and Moin (2008) reported that enthalpy (fuel mass fraction and/or temperature) fluctuations in the oncoming mixture have important impacts on premixed combustion and in particular on combustion instability. An analytical model for premixed combustion was derived from the reactive Navier-Stokes equations by using large-activation-energy analysis (AEA) that introduced the concept of flamelets to help in understanding laminar flames. The model gives insight into the premixed combustion, but is not suitable for vehicle control applications because of its complexity.

Ni and Henclewood (2008) presented the seminal Bernoulli model of internal combustion engines for vehicle infrastructure integration-enabled in-vehicle applications of high accuracy. The proposed model provides insight into the relation between engine power and the rate of fuel consumption, and it was validated successfully using empirical data. Yet, the model is not simple enough to be suitable for control and transportation applications.

2.2.2 Empirical models

Empirical modelling, or sometimes called phenomenological modelling, has been adopted in many research papers in the field of powertrain modelling and control. For instance, Hrovat and Sun (1997) presented linear internal combustion engine models and control design methodologies for the idle speed control (ISC) application. They reported that the application of modern ISC techniques, such as sensitivity tuning controls, has led to improved engine performance at idle speed. They highlighted the criticality of controlling the transition from/to the ISC mode. Though the models that are presented in that research paper give insight into the relation between the idle speed and the rate of fuel consumption, they are valid only for the driving condition of idling.

Yoon et al. (2000) presented a non-linear model of the dynamics of SI engine over a wide range of operating conditions. The model included intake manifold dynamics, fuel film dynamics, and engine rotational dynamics with transport delays inherent in the four stroke engine cycles. Yet, it is valid only for SI engines and does not account for compression ignition engines.

Puleston et al. (2002) proposed a model of air-fuel ratio (AFR) and engine speed using dynamic sliding mode (SM) control design methods. The proposed model is built using look-up tables representing parameter characteristics obtained from experimental data. The proposed model proved to be robust to model uncertainties and unknown disturbances, regulating effectively the engine speed for a wide range of set-points while maintaining the AFR at the stoichiometric value. However, the model does not provide explainable mathematical trends.

Wagner et al. (2003) proposed a model for determining the mass of air drawn into a given cylinder of an internal combustion engine using the engine speed, manifold absolute pressure, and inlet air temperature. In that study, a non-linear model-based control strategy was proposed for corresponding appropriate fuel amount and speed tracking in hybrid electric vehicles (HEV). The underlying engine model described the air intake, fuel injection, and rotational dynamics. Yet, that model is valid only for the range of data based on which it was built.

Sim and Sunwoo (2004) presented a model of the dynamics of a gaseous-fuel engine to predict the dynamic characteristics to be affected by components in mixture such as variations of the air flow, manifold pressure, and the AFR according to the water vapour and the gaseous fuel in the mixture. Although the model identifies a relation between the rate of fuel consumption and numerous dynamic characteristics of the internal combustion engine, it does not provide explainable mathematical trends.

Sciarretta et al. (2004) proposed a model-based strategy for the real-time load control of parallel hybrid vehicles. The model is intended to develop a fuel-optimal control. However, the model is valid only for the range of data based on which it was built.

Scillieri et al. (2005) addressed the ISC problem in the stratified charge mode of the direct-injection (DI) SI engine and cast it as a two-input-two-output control problem and a baseline feedback controller. Significant delays, however, hindered transient response improvement via feedback alone and thus an improved scheme employing reference feedforward was proposed in that paper. Yet, that study is valid only for SI engines and idling operating condition.

Chang and Morlok (2005) addressed the question of what speed profile will minimise vehicle fuel consumption. They proved that fuel consumption is approximately minimised by operating the vehicle engine at constant speed. Although that conclusion is helpful under cruising operating condition, it does not account for transient conditions.

Pu and Yin (2007) presented a mathematical model of optimal control of vehicle fuel economy. They proposed a cost function on the effect of frequent gear shifting and engine stop-starting on drivability and fuel economy. In order to overcome the problem of dimensionality of numerical dynamic programming (DP), an algorithm restricting the region to be explored was proposed in order to reduce the computational complexity. In that research, the system model was converted into a real-time simulation code using MATLAB/RealTimeWorld. Yet, the model does not provide explainable mathematical trends.

Ni and Henclewood (2008) presented two empirical engine models for vehicle infrastructure integration-enabled in-vehicle applications of reasonable accuracy, simplicity and computational efficiency. The two proposed empirical models, which are the Genta's polynomial model and the Genta's parabolic model originally proposed by Genta (2003), were validated successfully using empirical data. Albeit these two empirical models give insight into the relation between engine power and the rate of fuel consumption, they need calibration on peak power, peak torque, and their associated engine speeds.

Lindhjem et al. (2004) presented the physical emission rate estimator (PERE) which has been developed to complement the MOVES GHG emissions model for increasing the level of accuracy in estimating on-road vehicle emissions. They proposed under the sponsorship of the US EPA the PERE as an empirical model that is partly based on the principles of physics to estimate on-road vehicle emissions. Yet, that proposed model is valid only for the range of data based on which it was built.

Pitchford and Johnson (1993) proposed an empirical model that characterises the relationship between equilibrium vehicle emission distributions and malfunction, repair, and replacement rates by splitting vehicles into two emission categories. In that model, gross emitters and clean vehicles are defined by the magnitude of their emissions compared to an arbitrarily chosen cut point. Though the model was validated to predict emission changes satisfactorily, it does not provide explainable mathematical trends.

Rakha et al. (2010) developed a simple vehicle driveline model that can be integrated with car-following models within microscopic traffic simulation software. That empirical model is calibrated using engine and driveline parameters that are publicly available without the need for field data collection. The model demonstrated the capability to produce vehicle acceleration, speed, position, and fuel consumption estimates that are consistent with field observations.

Cook and Powell (1987) briefly reviewed the non-linear modelling of internal combustion engines literature and presented a fundamental non-linear model of an internal combustion engine. They found that non-linear dynamic models are suitable for wide speed and load operating ranges and seminal in the control of engine dynamics were developed by Powell (1979), Delosh et al. (1981), and Dobner (1980). They found as well that Wu et al. (1984) developed a similar non-linear model with experimentally based dynamic intake manifold fuel wall-wetting condensation effects. They presented a linear control-oriented model derived from the non-linear process based on Powell's model. Their model contains descriptions for the induction process and engine power system as well as characterisation of the fuel system and was validated experimentally.

Brandstatter (1985) had conducted experimental work on flow modelling to study the effect of engine configurations such as piston bowl, valve profile, manifold configurations, inlet manifold duct length, pent roof piston, etc. Brandstatter validated that model satisfactorily. Although the model provides insight into the influence of the engine's configuration on the engine's performance and on the rate of fuel consumption, it is valid only for the range of data based on which it was developed.

Chen et al. (1998) investigated empirically the effect of the flow of air through the manifold and of the mixing of the fuel with air inside the cylinder on the volumetric efficiency, combustion performance, output and emission levels of the engine. They proved that parameters like engine speed, manifold and combustion chamber configuration directly influence the swirl in DI diesel engines.

Dohner (1980) developed a mathematical model of a four-stroke spark-ignition engine for application to dynamic engine control. The model responds to throttle, air/fuel ratio, EGR, spark advance, and load torque inputs to satisfactorily provide manifold pressure, net torque, and engine speed outputs. However, it is valid only for spark-ignition engines.

Powell et al. (1998) described the mathematical modelling, analysis, and simulation of a dynamic automatic transmission and manual dry clutch combination powertrain model. Both the conventional powertrain model and hybridised powertrain model were simulated and validated using experimental test data. The model gives insight into what influence the rate of fuel consumption, but it does not provide explainable mathematical trends.

Mianzo (2000) developed a vehicle transmission model that was developed for the Visteon Powertrain Hardware-in-the-Loop (HiL) Project. The transmission model was used to verify the on-board diagnostics (OBD-11) and transmission control logic faster while satisfying strict emissions and fuel economy regulations. Yet, the model does not comprehensively describe the physical phenomena associated with the operation of the vehicle transmission and emission production.

Eriksson (2007) proposed a component-based modelling methodology for turbocharged engines. Using this methodology, Eriksson, developed models for the engine turbocharger compressor efficiency, compressor flow, and turbine flow. It was reported in that research these models can be used satisfactorily in observer design and air/fuel ratio control of SI engines, as well as in control design of direct injection (DI) engines with variable geometry turbine (VGT) and EGR.

Nilsson et al. (2008) presented a model of a variable compression diesel engine to capture the effects of ignition and compression ratio on the diesel engine torque. The main task for this model is to determine the fuel optimal control signals for each requested engine torque and speed. The model was validated experimentally with an error percentage of 1.2% only. However, it does not provide explainable mathematical trends.

Jankovic et al. (2000) developed input-output linearisation and reduced order form of a third order turbocharged diesel engine model. In addition, they developed based on that model a non-linear control Lyapunov function (CLF) the control objective of which is to regulate the AFR in the EGR and the fraction of re-circulated exhaust gas in the VGT to their respective set points that depend on engine operating conditions. Possible loss of robustness due to the cancellations used for the input-output linearising control was avoided because the controller's final control law does not depend on the intermediate feedback transformations used in constructing it. Yet, the model is valid only for the range of data based on which it was built.

Stefanopoulou et al. (2000) investigated an emission reduction control problem for a turbocharged direct injected diesel engine equipped with EGR and VGT. They reported that the control objective was to operate the engine to meet driver's torque demand and minimise NOx emissions while at the same time avoiding visible smoke generation. Thus, they proposed coordinating the EGT actuator and the VGT actuator to fully utilise their joint effect on engine emission performance.

Moulin and Chauvin (2009) proposed a turbocharging controller based on feedback linearisation of a simplified model of the turbocharger of a four-cylinder engine. The model helps in reducing CO_2 emissions in the automotive industry by decreasing the size of the engine while increasing its efficiency. However, the model does not provide explainable mathematical trends.

Filipi and Assanis (2001) developed a transient, non-linear, single-cylinder turbocharged diesel engine model for predictions of instantaneous engine speed and torque. The model is the transient version of the seminal semi-empirical, thermodynamic, steady state turbocharged diesel engine model proposed by Assanis and Heywood (1986). The transient extension of the parent model represents the diesel engine as a non-linear, dynamic system and provides an insight into the relation between the rate of fuel consumption, engine speed, and torque. Yet, the model is valid only for the range of data based on which it was developed.

Assanis and Heywood (1986) proposed a seminal semi-empirical, thermodynamic, steady state turbocharged diesel engine model. In that model, quasi-steady gas flow and heat flow models of the compressor, turbines, manifolds, intercooler, and ducting are coupled with a multi-cylinder reciprocator diesel model. The model was experimentally validated successfully against experimental engine test data. It gives insight into what influence the rate of fuel consumption but it does not provide explainable mathematical trends.

Jennings et al. (1986a) developed a comprehensive simulation model of Detroit Diesel Allison heavy duty diesel engines which describes the dynamic behaviour of truck powertrains. The model was developed to address those issues related to diesel electronic fuel control that impact upon engine smoke production and upon vehicle driveability and responsiveness, and to identify components in the powertrain which interact with the diesel electronic fuel control system. Jennings et al. (1986b) further validated this model and demonstrated its applicability of dynamic simulation to evaluating and optimising diesel engine performance. Yet, the model is valid only for diesel engines.

Flower and Gupta (1974) proposed a discrete-model of turbocharged diesel engines in the state-space form. Optimal controls, such as optimal fuel consumption rate control, were then developed based on the proposed model using both DP and discrete minimum principle techniques. However, the model does not provide explainable mathematical trends.

Watson et al. (1980) developed an empirical correlation simulating the turbocharged diesel engine's combustion process (heat release) via a mathematical expression whose governing parameters are linked to in-cylinder conditions. The proposed fundamental model provides the combustion information at the operating point and has become key in modelling combustion in diesel engines providing insight into what influence the rate of fuel consumption (Kim et al., 2002). Yet, it is valid only for the range of data based on which it was developed.

Millington and Hartles (1968) proposed a simple formula that correlates friction losses in diesel engines with firing conditions using loss measurements for a number of automotive diesel engines of all sizes. This model has become a fundamental model in modelling friction losses under firing conditions in diesel engines (Kim et al., 2002).

Albeit the model gives insight into combustion timing and into what influence the rate of fuel consumption, it does not provide explainable mathematical trends.

Delagrammatikas and Assanis (2001) proposed a systematic approach to preliminarily design diesel engines in automotive powertrains. In this approach, realistic constraints on the diesel engine's design are set through parametric studies and applied to an optimisation problem within the ADvanced VehIcle SimulatOR (ADVISOR) to find the minimum torque envelope for a given application. This torque limit is then applied to an engine matching problem within the simulator in a sequential manner to find the smallest, and thereby, most fuel-efficient, engine that would supply the necessary power and torque requirements for the specified application.

Killingsworth et al. (2006) proposed a simple model of the HCCI's combustion process that provides an estimate of the combustion timing on a cycle-by-cycle basis. An ignition threshold, which is a function of the in-cylinder temperature and pressure, is used to predict start of combustion which influences fuel consumption and emission rates. Yet, the model does not provide explainable mathematical trends.

Shyani and Caton (2009) presented a simulating model of the thermodynamic engine cycle of a SI engine with EGR that is used to reduce combustion temperatures and nitrogen oxide emissions. Using that model, it was found that for both a cooled and an adiabatic EGR configuration, the thermal efficiency first increased, reached a maximum, and then decreased as the EGR levels increased. However, the model is valid only for spark-ignition engines.

Shaver et al. (2006) reported that due to dilution limits, the HCCI engines will need to switch to a conventional SI or diesel mode at very low and high load conditions. Thus, they developed a simple control-oriented model of a single-cylinder multi-mode HCCI engine using exhaust reinduction. The model helps in controlling exhaust emissions but it does not provide explainable mathematical trends.

Bengtsson et al. (2004) reported that the operation of the HCCI engines is very sensitive to ignition timing variations. Thus, they presented a simple auto ignition model to predict the timing behaviour of HCCI engines at low load. The model is a lumped chemical kinetic model for hydrocarbon fuels to predict auto ignition which influences fuel consumption and emission rates. Yet, the model does not provide explainable mathematical trends.

2.2.3 Statistical models

Many researchers have preferred statistical modelling to other types of modelling in vehicle powertrains modelling for the advantageous features of this type that include quantifying uncertainty. For example, Biggs and Akcelik (1987) managed to evaluate the effect of vehicle characteristics on fuel consumption using a basic energy-related model of instantaneous fuel consumption and using field data. They explained the effects of engine capacity and mass on the parameters of the model. However, the model requires recalibration with each dataset.

Lindhjem et al. (2004) presented the MOVES GHG emissions model for on-road vehicle emissions. They proposed under the sponsorship of the US EPA a statistical model for modelling the on-road vehicle emissions. In that research, important vehicle operating parameters, such as engine speed, road grade, and vehicle weight are incorporated and explained. Yet, that model is valid only for the range of data based on which it was built.

Cacciari and Piancastelli (2001) presented a lumped mass model that is able to estimate velocity, acceleration and fuel consumption starting from aerodynamic, inertia and thermodynamic data of the vehicle. The model was then used along with a genetic algorithm (GA) to optimise the engine choice and the gearbox speeds distribution. That model is the base for their proposed robotised manual gearbox. However, the model does not provide explainable mathematical trends.

Pisu and Rizzoni (2007) reported that scalable models for the efficiency characteristics of component sizing in internal combustion engines, such as the fuel injection pump, have been developed by Rizzoni et al. (1999) and by Wei and Rizzoni (2001). In order to avoid dependence on the availability of specific efficiency maps for internal combustion engines and for electric motors to optimise and to formulate strategies of optimal control for HEV, a universal representation of these devices has been investigated by Brahma et al. (2000), Rizzoni et al. (1999), and Wei and Rizzoni (2001). They derived from these models a simple yet fairly accurate representation of internal combustion engines' efficiency.

Rakotomamonjy et al. (2007) developed a model for online calculation of torque values from the gear, the accelerator pedal position and the engine rotational speed. The model is based on the availability of input-torque experimental signals that are pre-processed (re-sampled, filtered and segmented) and then learns using a statistical machine-learning method. Although the model reached the error percentage of only 2%, it is valid only for the range of data based on which it was developed.

Ouladsine et al. (2004) presented a neural network-based model of a turbocharged diesel engine. The model is composed of three interconnected neural sub-models, each of them constituting a non-linear multi-input single-output output error model. In that model, the parameter estimation is done based on data gathered from a real diesel engine or on static mapping. Albeit the model gives insight into what influence the rate of fuel consumption, it requires recalibration with each dataset.

Wahlstrom (2005) developed a model of an internal combustion engine equipped with VGT and EGR. It was reported that the torque produced by this engine's model demonstrates some model errors probably because of the difficulty of modelling the non-linearity of the engine VGT and EGR and of capturing the effect of changing the engine speed on the VGT and EGR and thus on exhaust emission rates.

Zito and Doré Landau (2005) developed a high pressure direct injection (HDI) variable geometry turbocharged diesel engine model with VGT and without EGR. The proposed model is based on a non-linear black-box identification procedure that is in turn based on a polynomial NARMAX representation for modelling non-linearities. Yet, the model requires recalibration with each dataset.

Brace et al. (1994) explored the use of neural networks and related non-linear identification techniques for diesel engine modelling. They reported the effectiveness of neural networks in modelling diesel engines and capturing their non-linearities in many aspects such as fuel consumption and emission rates. These research findings were supported by the research findings of Rachid et al. (1994) and Dovifaaz et al. (2002).

Rizzoni (1989) investigated the effects of cyclic combustion variability on the cycle-to cycle and cylinder-to-cylinder fluctuations in combustion pressures. Rizzoni, proposed a deterministic model for the dynamics of the engine, and a stochastic model for the pressure building-up process. The deterministic model and the stochastic representation were then combined in a Kalman filter model. Though the proposed model helps in better understanding what influence the rate of fuel consumption, it requires recalibration with each dataset.

Daw et al. (1996) proposed a simple model that explains important characteristics of cyclic combustion variations in spark-ignited engines, such as the variations in the rate of fuel consumption. A key model feature is the interaction between stochastic, small-scale fluctuations in engine parameters and non-linear deterministic coupling between successive engine cycles. Yet, that model is valid only for the range of data based on which it was developed.

Wagner et al. (2001) modelled deterministic relations for cycle-to-cycle dynamics in spark-ignition engines with the development of physics-based mapping functions. That integrated-map model relates masses of air and fuel, lumped on a cycle basis, with feedback from cycle-to-cycle via the cylinder residual gases. The research findings of this model were upheld by the findings of Sutton (2000). However, mapping-based modelling is sometimes not satisfactory because emission maps can be highly sensitive to the driving cycle.

Daw et al. (2009) extended an iterated-map model that relates masses of air and fuel, lumped on a cycle basis, with feedback from cycle-to-cycle via the cylinder residual gases to spark assisted HCCI combustion. This extended model combines diluent-limited flame propagation (SI) and temperature-dependent, residual gas driven combustion (HCCI) to compute a combustion extent and integrated heat release for each cycle. Although such mapped model can approximate the global dynamics of the combustion oscillations, it does not employ any chemical-kinetic relations in their solution.

Bancha and Jau-Huai (2009) reported that HCCI operation begins from aspirating of homogeneous charge mixture through intake valve like SI engine and the premixed charge is compressed until temperature and pressure of mixture reach auto ignition point like diesel engine. Thus, they developed a single-zone model to predict the temperature and the pressure variation in an internal combustion engine operated in HCCI mode providing insight into what influence the rates of fuel consumption and emissions. Although the modelling prediction error was 6%, that model requires recalibration with each dataset.

2.2.4 Graphical models

Graphical modelling has been widely chosen in numerous research papers to model vehicle powertrains. For instance, Butler et al. (1999) presented 'V-Elph' vehicle engine model that is composed of four components: electric motors, internal combustion engines, batteries, and support components that can be integrated into a model and can simulate drive-trains. V-Elph was written in the Simulink graphical simulation language and is portable to most computer platforms. The model is intent to predict vehicle fuel consumption and vehicle emissions. However, the accuracy of prediction of that model is not high.

Gao et al. (2007) presented a physics principles-based resistive companion form technique and bond graph method with a powertrain component. They presented as well the modelling and simulation capabilities of existing tools such as powertrain system analysis toolkit (PSAT), advanced vehicle simulator (ADVISOR), PSIM, and virtual test bed. These modelling methods and tools are helpful in predicting fuel consumption and emission rates. However, the models that these tools provide do not provide explainable mathematical trends.

Grossi et al. (2009) modelled an internal combustion engine using the power-oriented graphs (POG) technique with analogy between engine description and electrical circuit. They found that there is modelling correspondence between the engine components and variables (e.g., throttle valve, cylinder, and inertial flows) and electrical counterparts (e.g., current, voltage, and resistance). Albeit the model gives insight into what influence the rate of fuel consumption, its accuracy is not high.

Silverlind (2001) presented the Modelica software package which is a seminal library of basic and flexible components suitable for developing mean value engine models (MVEMs) and control algorithms for the evaluation of new hardware on the systems-level, such as the fuel injection system in the internal combustion engines. The Modelica software package provides a structured means to develop a MVEM and is originally developed for DaimlerChrysler.

Stankovic (2000) presented 'Modelica' as a standardised, object-oriented, and multi-domain modelling language for modelling the automotive engines thermodynamic subsystems, such as the fuel injection sub-system. Stankovic analysed the performance of Modelica in automotive engine applications. It was identified that the modelling principle in Modelica is based on the connector applied, i.e., the interaction between the components, for the description of engine components.

Elmqvist et al. (2004) described typical modelling and real-time simulation issues that occur in vehicle powertrain dynamics modelling. In addition, they demonstrated the powerful real-time capabilities of Dymola and the Modelica modelling languages and their symbolic processing of the model equations.

Kim and Kim (1999) developed a computational fluid dynamics model of a large diesel engine using the WAVE software package to predict combustion heat release rate from user-specified fuel injection rate and injector geometry. The model was simulated and verified by experimental data of heat release rate and NOx emission for Hyundai Heavy Industries Co., Ltd. Yet, that model does not provide explainable mathematical trends.

Mukherjee and Karmakar (2000) presented the modelling and simulation of physical dynamic systems through bond graphs portraying systems in terms of power bonds. They presented bond graph as a graphical representation of a physical dynamic system, such as vehicle engines, with the major difference from block diagrams that the arcs in bond graphs represent bi-directional exchange of physical energy, while those in block diagrams and signal-flow graphs represent uni-directional flow of information. The engine model is generated using a modelling environment that supports hierarchical structuring by means of bond graphs (Louca et al., 2001).

Gissinger et al. (1989) described a graphical approach for the complete modelling of a diesel engine. They used bond graphs to model and simulate the behaviour of a turbocharged six cylinder diesel engine. The programme handles the various non-linearities such as the non-linearity of the rate of fuel consumption, the various coolants, the heat transfers within the cylinder head and the ignition delays.

Simulink is a similar multi-domain simulation and modelling software package that was developed by Mathworks Inc., and has become a widespread engine modelling tool in industry (The MathWorks Inc., 2000; Eriksson et al., 2010). Its primary interface is a graphical block diagramming tool and a customisable set of block libraries that let designers model a variety of time-varying systems. The platform provides reusable generic components in a library for developing engine models setting standardised rules for modelling dynamic systems, such as the fuel injection pump of internal combustion engines.

Assanis et al. (2000) developed a Simulink integrated model of vehicle systems composed of turbocharged, intercooled diesel engine, driveline and vehicle dynamics modules. The engine model features the thermodynamics of the in-cylinder processes with transient capabilities to ensure high fidelity predictions and was validated successfully. However, it does not provide explainable mathematical trends.

2.3 Main input variable-based modelling

Modelling of vehicle fuel consumption and emissions rates can be categorised as well based on the main input independent variable. In this type of categorisation there are three subcategories:

1 modelling based on average speed as the main input independent variable

2 modelling based on instantaneous speed as the main input independent variable

3 modelling based on specific power as the main input independent variable.

These three subcategories will be elucidated in this section.

2.3.1 Average speed models

Average speed is the most widely used independent input variable in vehicle fuel consumption and emission rates modelling. Many research papers adopted average speed as the main independent input variable in vehicle fuel consumption and emission rates modelling. Ding and Rakha (2004) identified recent state-of-practice for estimating vehicle emissions based on average speed only. They found that research has demonstrated that although the EPA MOBILE5 model would indicate that slowing of traffic typically increases emissions, empirical research indicates the opposite in many cases. They proposed statistical models for estimating fuel consumption and emissions using average speed as a critical input variable. Though these models were validated successfully, they require recalibration with each dataset.

Another research work that adopted average speed as the main independent input variable in vehicle fuel consumption and emission rates modelling is the research done by Evans and Herman (1978). In that research, they found that the differences in fuel economy measured using different schedules can be satisfactorily explained in terms of a simple model, relating fuel consumption to the average speed of urban traffic, previously derived by driving instrumented vehicles in actual street traffic. However, the model does not account for the significant effect of speed variability on vehicle fuel consumption and emission rates.

Guensler et al. (1993) further explored adopting average speed as the main independent input variable in vehicle fuel consumption and emission rates modelling. They proposed disaggregate SCF modelling technique to estimate relationships between average speed and vehicle emissions. Yet, the results indicate that additional data should be collected and that additional independent variables should be included. Thus, they found that average vehicle speed as the single explanatory variable is insufficient for modelling emissions.

Taylor (2003) presented CONTRAM which is a computer model of time-varying traffic in road networks that takes as input the network definition and time-varying demand for travel between a set of origin and destination zones, and delivers as outputs the resulting network flows, routes and travel times. The paper detailed the central method used in this model which is the time-dependent queuing. In addition, it presented an empirical fuel consumption and emissions model based on Everall's function of average speed and fuel consumption. Although, this average speed model is helpful in estimating aggregate emissions inventories and highly relevant to road traffic, it ignores the effect of transient changes in vehicle speed and acceleration.

Kent and Mudford (1979) presented a model to predict emissions and fuel consumption of motor vehicles. In that study, 28 vehicles were tested on a dynamometer to obtain the modal emission rates of pollutants. Interestingly, nitrogen oxides were almost independent of average speed and showed more scattered patterns than other pollutants.

Anderson et al. (1996) presented an integrated urban model called IMULATE produces estimates of traffic flows and average speeds on each link in an urban road network using a user equilibrium assignment algorithm. The integrated urban model, IMULATE, was developed in order to be interfaced with the MOBILE5 emission model providing the key inputs for the MOBILE5 model. Yet, IMULATE does not account for the significant effect of speed variability on vehicle fuel consumption and emissions rates.

Smit and McBroom (2009) presented the development of a statistical high-resolution traffic emissions and fuel consumption average speed model. They suggested the use of different combinations of other prediction variables such as power functions. Albeit the model was validated satisfactorily, it requires recalibration with each dataset.

Rizzotto et al. (1995) presented a data-based fuzzy logic bus fuel consumption model. The results of fuel consumption measurements in that research were correlated to a set of independent variables which represent the vehicle average speed, number of passengers on board, and the actual elevation of the road. They reported that fuzzy logic is more efficient in correlating measured data than traditional mathematical method such as least squares.

Liao and Machemehl (1998) suggested an average speed-based analytical fuel consumption model (AFCM) to estimate the effects of signal timing on fuel consumption at signalised intersections. The AFCM describes how fuel is consumed on three street segments (inbound approach, intersection itself, and outbound leg) for three signal cycle stages (the effective red time, queue departure time, and remaining green time). In that research, results of numerical experiments conducted using the AFCM were compared with results from the TEXAS simulation model with 10% error. However, the AFCM does not account for the significant effect of speed variability on vehicle fuel consumption and emissions rates.

Newman et al. (1989) presented a statistical and data-based fuel consumption model that uses average speed, engine displacement, and vehicle mass to predict fuel consumption for petrol and diesel trucks. They found that the vehicle mass is the term that dominates the influence on fuel consumption. The model they presented is of relatively moderate accuracy with 20% error.

2.3.2 Instantaneous speed models

Instantaneous speed is the second most widely used independent input variable in vehicle fuel consumption and emission rates modelling. Many research papers adopted instantaneous speed as the main independent input variable in vehicle fuel consumption and emission rates modelling. Rakha and Ahn (2004) proposed that average speed is insufficient to fully capture the environmental impacts of ITS. They found that for the same average speed, one can observe widely different instantaneous speed and acceleration profiles, each of which results in very different fuel consumption and emission levels. Thus, they developed a software package called INTEGRATION model that combines car-following, vehicle dynamics, lane changing, energy, and emission models to estimate mobile source emissions from instantaneous speed and acceleration levels. The validity of the model was demonstrated using sample test scenarios that include travelling at a constant speed, travelling at variable speeds, stopping at a stop sign, and travelling along a signalised arterial.

Ahn et al. (2002) proposed statistical regression models that predict vehicle fuel consumption and emission rates with key input variables of instantaneous vehicle speed and acceleration measurements. The energy and emission models described in that paper utilised data collected at the Oak Ridge National Laboratory (ORNL) that included fuel consumption and emission rate measurements (CO, HC, and NOx) for five light-duty vehicles and three light-duty trucks as a function of the vehicle's instantaneous speed and acceleration levels. The fuel consumption and emission models developed in that research were found to be relatively accurate as compared to the ORNL data, with coefficients of determination ranging from 0.92 to 0.99. The study indicated that since these models utilise the vehicle's instantaneous speed and acceleration levels as independent variables, they are capable of evaluating the environmental impacts of operational-level projects including ITSs. In addition, the study incorporated these models into the INTEGRATION microscopic traffic simulation software to further demonstrate their application and relevance to the transportation profession. The study further indicated that these models were utilised in conjunction with global positioning system speed measurements to evaluate the energy and environmental impacts of operational-level projects in the field. Yet, these proposed models require recalibration with each dataset.

Rakha and Van Aerde (2000) reported that the evaluation of many transportation network improvements commonly is conducted by first estimating average speeds from a transportation or traffic model and then converting these average speeds into emission estimates based on an environmental model such as MOBILE. Yet, recent research has shown that average speed is an insufficient measure to fully capture the impact of ITS strategies such as traffic signal coordination. They proposed a series of multivariate fuel consumption and emission prediction models that are applicable both to be used within a traffic simulation model of a signalised arterial and directly to instantaneous speed and acceleration data from floating cars travelling down a similar signalised arterial. The study indicated that the application of these instantaneous models is more practical in terms of both their absolute magnitude and their relative trends than of average speed-based models.

Ahn (2002) presented the Virginia Tech Microscopic model (VT-Micro) that predicts the instantaneous fuel consumption and emission rates of HC, CO and NOx of individual vehicles based on their instantaneous speed and acceleration levels. Key input variables to the VT-Micro model include instantaneous vehicle speed and acceleration levels. That model captures transient changes in a vehicle's speed and acceleration level as it travels on a highway network.

Panis et al. (2006) modelled the traffic emissions caused by acceleration and deceleration of vehicles based on an instantaneous emission model integrated with a microscopic traffic simulation model. Their proposed integrated model captures the second-by-second speed and acceleration of individual vehicles. However, it is very labour intensive in conducting inventory analysis.

Zweiri et al. (2001) developed a detailed non-linear dynamic model for single-cylinder diesel engines. The model describes clearly the dynamic behaviour and inter-relationships between fuelling and engine speed. Albeit the model captures the second-by-second variations in the speed of the engine, it is relatively time consuming.

Hung et al. (2005) developed a data-based model of vehicular fuel consumption and emissions as a function of instantaneous speed and driving mode. They proposed piecewise interpolation functions for each non-idling driving mode in that model. Although this instantaneous speed-based model can capture transient changes in a vehicle's speed as it travels on a highway network, and is more accurate in estimating vehicle emissions than average speed models, it is very labour intensive in conducting inventory analysis.

Ajtay and Weilenmann (2004) developed a new static instantaneous emission model compensating the transport dynamics from the engine to the analysers by time-varying approaches. They developed as well subsequently a dynamic instantaneous model that is able to include the transient generation of emissions while predicting engine-out emissions. Though these models were validated satisfactorily, they are relatively time consuming.

Froschhammer et al. (2006, 2009) presented cost-effective component-based SIMPACK real-time engine models used by the BMW Group. The term 'component-based' refers to models which include individual components, such as valves, as opposed to using quasi-static look-up tables to describe the engine's characteristics. The models showed satisfactory performance, but they have relatively moderate computational efficiency.

dSPACE GmbH (2006) presented a dSPACE real time diesel engine model and HIL simulator implemented for Deutz AG. The presented model and simulator provides wide engine variants handling and easy engine test automation. Albeit the model was validated satisfactorily, it is relatively time consuming.

Ball et al. (2000) proposed a single degree of freedom torsional model of a four-cylinder internal combustion engine using the instantaneous angular acceleration developed in the engine block as an input to the model in order to detect misfires, which significantly affect fuel consumption and emission rates, and to estimate indicated torque. Results indicate that the resulting metrics based on low frequency information were most reliable. Yet, the model seems less practical for vehicular applications at high engine speeds.

2.3.3 Specific power models

Specific power is the third most widely used independent input variable in vehicle fuel consumption and emission rates modelling. Many research papers adopted specific power as the main independent input variable in vehicle fuel consumption and emission rates modelling. Frey et al. (2007) proposed a vehicle specific power (VSP)-based approach to be used for modelling fuel consumption for diesel and hydrogen fuel cell buses. In that research, relative errors between trip fuel consumption estimates and actual fuel use were generally under 10% for all observations. The study recommended the VSP-based modelling approach if the relevant data are available.

Ran et al. (2007) presented a mean specific power-based model of hydrogen fuelled spark-ignition internal combustion engines for design and sizing of such engines. The study concluded that the mean value based sizing and simulation model gives relatively satisfactory sizing results. However, the model is valid only for SI engines.

Wang et al. (2008) presented a data-based VSP-based model of vehicle fuel consumption to estimate the influence of driving patterns on fuel consumption using a portable emissions measurement instrument. They found that fuel consumption increases significantly with acceleration. Although this specific power model has reasonable accuracy, it is valid only for the range of data based on which it was built.

Song et al. (2009) proposed a model for evaluating the effects of traffic management on fuel efficiency of light duty vehicles. The model captures the relationships between the VSP, the real world driving activities, and the corresponding fuel consumptions. However, that model needs availability of relevant specific power data.

Feng (2007) developed a new heavy-duty diesel vehicle load-based modal emission rate model that is called heavy-duty diesel vehicle modal emission modelling (HDDV-MEM). The HDDV-MEM approach first predicts second-by-second engine power demand as a function of vehicle operating conditions and then applies brake-specific emission rates to these second-by-second engine power demand predictions. Albeit the model was validated satisfactorily, it is valid only for diesel engines.

2.4 State variable value-based modelling

Another classification of modelling of vehicles' fuel consumption and emissions is the state variable value-based modelling. This classification has two subcategories: crank-angle resolution-based models and mean value-based models, as suggested by Guzzella and Amstutz (1998). Cook et al. (2006) reported as well that diesel engine models can be classified into mean value modelling and cylinder-by-cylinder modelling, i.e., analytical modelling. The mean value modelling of diesel engines, its average value of states characteristic, and its simplicity and easiness of manipulation were presented and covered by Kao and Moskwa (1995). The cylinder-by-cylinder modelling, its crank angle resolution characteristic, and its explainable trends were presented and covered by Watson (1984). It predicts the effects of mechanical and/or control system changes on vehicle powertrain output torque, fuel consumption, and emission using the state of the crank-angle resolution. The mean value-based models predict these effects based on the mean value of the state variables within the vehicle powertrain system. This section presents these two subcategories in more details.

2.4.1 Crank-angle resolution-based models

Crank-angle resolution-based models have been used for long time for modelling vehicle powertrain fuel consumption and emission rates. Many researchers adopted this type of modelling for its accuracy. Guzzella and Amstutz (1998) presented model-based controls of diesel engine torque and transient macroscopic pollutant emission. They identified the tendencies in the influence of control inputs to diesel engines on the brake specific fuel consumption and emissions. They found that adopting early start of injection as a control input results in good brake specific fuel consumption and reduced amount of particulates but at the expense of high NOx emissions. They found as well that late start of injection results in reduced NOx emissions but at the expense of an increase in brake specific fuel consumption and particulate emissions. They reported that model classification must distinguish between:

1 distributed models or lumped parameter models

2 crank-angle resolution models or cycle averaged models

3 formulation as mean-value models or as discrete event models

4 model complexity adapted to analysis or to controller design.

They reported as well that crank-angle resolution models of diesel engines, such as the models for heat release, wall heat losses, and scavenging, are very useful for performance prediction but are still too complex to be used for the purpose of control, and the corresponding effects would have to be pre-computed or measured and stored in appropriate 'maps'. Moreover, they found that the models that are classified under one of these reported classifications are usually too complex to be used for controller synthesis, and thus linear low-order models are preferred. Two types of linear low-order models are mostly used:

a parametric models, i.e., models that have been derived using physical first principle

b non-parametric models (sometimes called 'black box' models), i.e., models that use a priori chosen structure to reflect the input/output behaviour of the engine that has been experimentally analysed.

Streit and Borman (1971) presented a crankshaft resolution model of multi-cylinder turbocharged diesel engines. The model for the cylinder includes instantaneous heat transfer, homogeneous combustion burning rates explaining their relation to the rate of fuel consumption, and a scavenging model which allows any intermediate mode between perfect scavenging and complete mixing. They developed as well a model for the compressor of the turbocharger. Upholding the research findings of that research, Heywood (1988) reported the existence of a radiative heat transfer component during combustion. Though these models were validated satisfactorily, they require a relatively long computational time for their complexity.

Winterbone et al. (1977) developed a crank angle resolution model of turbocharged diesel engines based on the 'filling-and emptying' technique and using empirical feedback to estimate their transient response. The experimentally validated model was then used to evaluate the linearised transfer function of the diesel engine for control studies, such as fuel consumption control. However, the model needs to be simplified before being suitable for vehicle control applications.

Hillion et al. (2009) proposed a linearisation of the modified auto ignition KIM for HCCI and a cool flame model in order to accurately control the end of the cool flame phenomenon and thus improving the stability of the combustion of HCCI engines during transients as well as improving the control on fuel consumption. The modified auto ignition KIM for HCCI was originally proposed by Swan et al. (2006). The cool flame model models the combustion with a very low reaction rate during which several chemical processes occur simultaneously leading to the real combustion. Albeit these models demonstrated reasonable accuracy, they require a relatively long computational time for their complexity.

Lansky (2008) proposed a MATLAB-Simulink model of the cylinder of diesel engines for achieving a less polluting and more fuel-efficient combustion process. The model allows to simulate the cylinder pressure and temperature in crank-angle domain. The model was validated with an error percentage less than 15%.

Karlsson and Fredriksson (1999) investigated which one of the two categories of engine models which are crank-angle resolution models, which are sometimes called cylinder-by-cylinder engine models, and MVEMs is more suitable for the use in powertrain control applications. The way to evaluate the engine models was to compare the dynamical behaviour and how the engine affects the driveline. It was found that the MVEMs are compact enough to be suitable for powertrain control applications, such as fuel consumption and emission control.

Wang and Zhang (2006) reported that analytical diesel engine models can be classified into two classes:

1 crank-angle resolution models

2 mean-value models.

The first class models are most helpful in the performance prediction but are too complex to be used for the purpose of control (Guzzella and Amstutz, 1998). On the other hand, the mean-value models, such as the one presented by Hendricks in 1989, is widespread used for non-linear control and observation of diesel engine performance, fuel consumption, and emission due to its simplicity. However, the estimates of the mean-value models are usually less accurate than those of the crank-angle resolution models.

2.4.2 Mean value-based models

The other subcategory of the state variable value-based modelling classification is the mean value-based modelling. Mean value-based models have been adopted extensively in modelling vehicle powertrain fuel consumption and emissions rates for its high computational efficiency. Hendricks (1986) reported that the detailed analytical models of the internal processes in the engine are very accurate and very useful for detailed laboratory analysis of engine performance, but they require long computing times and exhibit large numbers of fitting parameters. Thus, Hendricks presented for the first time a model of the engine's dynamics that is called MVEM to predict the effects of mechanical and/or control system changes on heavy duty diesel engines output torque. This seminal model is a compact dynamic mean value model of the internal processes of large turbocharged two-stroke diesel engines which can run on a microcomputer and includes the main diesel engine non-linearities. Hendricks (1997) further proposed a mean value diesel engine's dynamics model that describes the transfers between inputs (e.g., the crankshaft angular speed and throttle valve angle) and the output (e.g., fuel mass flow). It is derived partly from basic physical and thermodynamic principles and seeks to predict the mean values of heavy duty diesel engine variables (e.g., volumetric efficiency and exhaust manifold pressure).

Karmiggelt (1998) proposed a hybrid control strategy based on estimating the produced engine output torque online using a MVEM. The inputs to that model are engine speed, the position of the throttle valve, and intake manifold pressure. The outputs from that model are the engine output torque and fuel consumption. The model was validated satisfactorily with a reasonable computational efficiency.

Jensen et al. (1991) developed a mean value model for the transient operation of a turbocharged indirect injection diesel engine. The model consists of a series of sub-models for the compressor, turbine, and engine. Although this model is suitable for control applications and is highly relevant to road traffic, it does not account for delays.

Seykens et al. (2006) presented the extension of the steady state mean value dynamic engine model (DYNAMO), proposed by Ewalds (2003), combining the compression release brake and an exhaust valve brake in order to predict engine brake torque, exhaust gas temperatures and air and fuel mass flow rates. The developed model has been used successfully to analyse the possibility to use the engine brake torque to make automatic gear switching smoother and faster. However, it is valid only for the range of data based on which it was built.

Moskwa and Hedrick (1992) presented a seminal non-linear DYNAMO of a port fuel-injected engine, which can be used for control algorithm development. This engine model predicts the mean engine brake torque as a function of the engine controls such as throttle angle. Moskwa (1988) proposed as well part-throttle shift in order to minimise clutch energy dissipation during a gear shift. He developed a mean-torque predictive non-linear port fuel-injected DYNAMO for designing a control algorithm to implement the proposed part-throttle shift. Albeit these models were validated satisfactorily, they do not account for delays.

Sun et al. (2005) presented the fundamental system models of the AFR and torque that are typically embedded into the engine control strategy for most engines. They presented as well the key issues in electronic control of internal combustion engines and their solutions. The research findings of that research were upheld by the findings of Zhao et al. (1997). Sun et al. (2005) reported that Assanis et al. (1999) proposed a predictive model of the wastegate of the turbocharger which consists of a spring-loaded diaphragm in the exhaust manifold. In addition, a mean value model of VGT diesel engines was developed by Kolmanovsky et al. (1997) for a diesel engine equipped with an EGR valve. Sun et al. (2005) highlighted as well the research finding of Canova et al. (2010) that two-stage turbochargers are a recent solution to improve engine performance and to mitigate the turbo-lag phenomenon although their modelling is problematic because of their complexity.

Eriksson et al. (2010) presented semi-physical mean value non-linear models of the dynamics and non-linear behaviours of gas and energy flows in EGR/VGT equipped turbocharged diesel engines. They found that the EGR system and VGT which were introduced to reduce emissions are strongly coupled and are difficult to be optimised because of their overshoots, non-minimum phase behaviours, and sign reversals which are upheld by the findings of Winge Vigild (2001).

Hendricks and Sorenson (1990) presented a seminal mean value non-linear dynamic model of the entire four-cycle SI engine subsystems including the fuel injection and exhaust subsystems. The model proved to have nearly the same steady state accuracy as much as for fast transients with 2% error. However, it is valid only for SI engines.

Hendricks (2001) presented a seminal adiabatic mean value model of SI engines and diesel engines. The proposed adiabatic mean value model described the performance, such as the rates of fuel consumption and emission, and dynamics of the engines with EGR more accurately than the conventional isothermal MVEMs. Yet, it does not account for delays.

Wahlstrom (2009) developed a mean value model of a turbocharged diesel engine for lowering emissions from heavy duty vehicles by coordinating the control of EGR valve and VGT position. They reported that the main goals of control through modelling which were achieved in this research are to fulfil the legislated emission levels, to reduce the fuel consumption, and to fulfil safe operation of the turbocharger. Although the model was validated successfully, it is valid only for diesel engines.

Eriksson et al. (2002) developed for Saab a mean value model of the following components of a turbocharged SI engines that do not exist in naturally aspirated engines: air filter, compressor, intercooler, throttle, engine, turbine, and wastegate. The model helps in evaluating the rate of fuel consumption. In addition, it includes a lumped model for the catalyst and exhaust. The model was validated experimentally using Saab engines yet it raised a number of technical issues.

Andersson and Eriksson (2004) developed mean value cylinder air charge (CAC) estimation models for control and diagnosis of turbocharged SI-engines. Using these proposed models, the CAC changes due to fuel enrichment and the CAC sensitivity to exhaust manifold pressure changes can be estimated satisfactorily. Yet, they do not account for delays.

Canova et al. (2009) proposed a control-oriented mean value model of HCCI combustion in diesel engines. The model includes a thermodynamic combustion calculation that estimates the heat release, cylinder pressure, and the relevant variables for combustion control, such as the rate and timing of fuel injection. Albeit the model was validated satisfactorily, it is valid only for the range of data based on which it was built.

Heywood (1994) reported that there are four main models of the combustion flame structure that helps in better understanding what influence fuel consumption and emission rates. The first main model of the flame structure is the mean flame speed model which is the simplest flame structure model to represent the turbulent flame by its mean contour location, which was presented by Wirth et al. (1993). The second main model of the flame structure is the kernel initiation model that was presented by Herweg and Maly (1992) and by Sher et al. (1992) in which the total process of flame kernel development is divided into sequential sub-processes through heat conduction to the surrounding gases. The third main model of the flame structure is the entertainment and burn-up flame model, which was presented by Blizard and Keck (1974) in which the burning-up process is described as occurring in two stages:

1 unburned mixture is entertained into the turbulent flame brush

2 burn-up within the flame brush.

The fourth main model of the flame structure is the flame sheet model which is based on estimating the surface area of the wrinkled thin reaction-sheet flame using a fractal geometric model as suggested by Gouldin (1987) or using coherent flame sheet model as suggested by Cheng and Diringer (1991).

Heywood (1994) reported as well that there are two main models of the combustion flame speed that gives insight on what influence the rates of fuel consumption and emission. The first main model of the flame speed is the laminar flame speed presented by Metghalchi and Keck (1980), and Rhodes and Keck (1985) in which the initial flame kernel growth is considered laminar and adiabatic. The second main model of the flame speed is the turbulent flame speed presented by Brehod and Newman (1992) in which the initial flame kernel growth is considered turbulent.

Cho et al. (2001) proposed AFR predictive model and a mean torque predictive model. It includes an inducted air mass sub-model, a fuel delivery sub-model and a mean torque production sub-model. Although the model was validated satisfactorily, it is valid only for SI engines and transient response.

2.5 Number of dimensions-based modelling

The subcategories of the number of dimensions-based modelling classification are zero/one dimensional/single zone, quasi dimensional, and multi-dimensional/multi-zone modelling, as suggested by Jung and Assanis (2001). The zero/one dimensional/single zone modelling assumes that the cylinder charge is uniform in both composition and temperature, at all time during the cycle which results in high computational efficiency (Foster, 1985). Multi-dimensional/multi-zone models, such as KIVA, account for spatial variation in mixture composition and temperature, which are essential to predict exhaust emissions (Bracco, 1985; Amsden et al., 1985; Varnavas and Assanis, 1996). The quasi dimensional modelling is an intermediate step between zero-dimensional and multi-dimensional models and can provide the spatial information required to predict emission products and require significantly less computing resources compared to multi-dimensional models (Austen and Lyn, 1961; Whitehouse and Sareen, 1974). These three subcategories will be elucidated in this section.

2.5.1 Zero/one dimensional/single zone models

When high computational efficiency becomes the first priority, zero/one dimensional/single zone modelling is preferred to other types of modelling due to its high computational efficiency. Thus, many researchers opt for this type of modelling in order to model vehicle powertrain fuel consumption and emission rates. Schmitt et al., (2009) described how a zero-dimensional engine model can improve the engine control law design for a turbocharged diesel engine fitted with an EGR system. Because of the simplicity of the zero-dimensional engine model, it proved to give a good estimate of the start of combustion with minimal computational time. This conclusion is supported by the findings of Aceves et al. (2001). The proposed model helps in developing diesel engine controllers to meet the Euro VI pollutant standard, while maintaining the fuel consumption advantage the diesel engines have compared to SI engines.

Şahin and Durgun (2008) developed a complete cycle model and a computer code for determining complete cycle, performance characteristics, and exhaust emissions of diesel engines. The model incorporates the following models as sub-modules:

1 zero-dimensional multi-zone intake and exhaust model developed for diesel fuel and light fuel fumigation analysis by Durgun and Sahin (2009)

2 zero-dimensional compression and expansion model developed by Heywood (1988)

3 quasi-dimensional, phenomenological, multi-zone, transient spray combustion model for estimating nitric oxide emission characteristics of a turbocharged diesel engine developed by Ottikkutti et al. (1991).

The model predictions closely matched the other theoretical models predictions and experimental data.

Liu and Chen (2009) developed a zero-dimensional combustion model for SI engine knock optimisation. The model helps in optimising the rate of fuel consumption and fuel injection timing. It is based on a three-zone approach (i.e., unburned, burning, and burned zones). A modified version of Tanaka's reduced chemical kinetic model for a commercial gasoline fuel was applied in both burned and unburned zones incorporated with the Loughborough University Chemical Kinetics Simulation (LUCKS) code. In the burning zone, an equilibrium combustion thermodynamic model is used. Yet, its accuracy is relatively low.

Tirkey et al. (2010) developed a zero dimensional knock model, two-zone combustion model, and gas dynamic model to minimise engine emissions and safe knock limit by optimising some operational and engine design parameters such as equivalence ratio. Therefore, the nitric oxide exhaust emission concentrations are then predicted using the rate kinetic model. Albeit the model was validated satisfactorily, the accuracy of this model is relatively low.

Arregle et al. (2003) developed a CFD zero-dimensional diesel combustion model for diesel engines. The model is composed of two parts:

1 the central phase of the quasi-steady diesel diffusion combustion

2 the final and initial transient phases of the diffusion combustion.

The model helps in better understanding what influence the rates of fuel consumption and emission. Although this model is simple and of high computational efficiency, it does not account for the spatial variation in mixture composition and temperature in the cylinder charge.

Sridhar et al. (2006) developed a zero-dimensional model using wrinkled flame theory for combustion flame propagation, in which the in-cylinder flow is considered turbulent with wrinkling eddies, to understand the in-cylinder pressure behaviour with time in a reciprocating internal combustion engine and to better understand what influence the rate of fuel consumption. The computational results matched reasonably well with experimental measurements with an error percentage of less than 10%.

Barba et al. (2000) presented a phenomenological single-zone combustion model for high speed DI diesel engines with common rail injection to help in meeting the emissions requirements for this type of engines. The model focuses on result parameters like combustion noise and NOx-emission which are affected by this fuel split injection. Although the model is suitable for modelling and powertrain control applications and is highly relevant to road traffic, its accuracy is relatively low.

Shrivastava et al. (2002) developed a CFD optimisation model for optimising the design of a direct-injection diesel engine using a 1D KIVA GA (1D-KIVA 3v-GA) computer code. The design fitness in this model was determined using a 1D gas dynamics code model for the simulation of the gas exchange process, coupled with a 3D code model of spray, combustion, and emissions formation. Though this model was validated satisfactorily, it does not account for the spatial variation in mixture composition and temperature in the cylinder charge.

Klein et al. (2004) reported that there are two main models for compression ratio estimation of an engine from cylinder pressure traces. The first one is called Polytropic model, presented by Klein and Eriksson (2002), which is a simple model for cylinder pressure trace and valid for adiabatic conditions, and works well during the compression and expansion phase of the engine cycle, but not during combustion since it lacks the information about heat transfer. The second one is called Levenberg-Marquardt and standard model, presented by Gatowski et al. (1984), which is able to estimate the compression ratio more accurately at low as well as high compression ratios since it is based on single zone modelling which includes heat transfer and crevice effects. These models help in improving fuel consumption efficiency.

2.5.2 *Quasi dimensional models*

The second subcategory of the number of dimensions-based modelling classification is the quasi dimensional modelling. Quasi dimensional modelling strikes a balance between modelling accuracy and modelling computational efficiency. Thus, many researchers preferentially adopt this type of modelling. Jung and Assanis (2001) developed a quasi-dimensional, multi-zone, DI diesel combustion model and implemented it in a full cycle simulation of a turbocharged engine. The combustion model accounts for transient fuel spray evolution, fuel-air mixing, ignition, combustion and NOx, and soot pollutant formation. It was proved that the model is capable of predicting the rate of heat release and engine performance with high fidelity, but it cannot predict NOx and soot emissions satisfactorily.

Bi et al. (1999) developed a quasi-dimensional multi-zone model for diesel spray combustion. This simple model contains most of the physical processes of diesel spray combustion that influence the rates of fuel consumption and emission. Although the model strikes a balance between modelling accuracy and computational efficiency, it does not account for large spatial variations in mixture composition and temperature in the cylinder charge. The same holds true for the experimentally validated quasi-dimensional multi-zone combustion model for DI diesel engines that emphasises the fuel evaporation process and was developed by Zhou et al. (2006).

Verhelst and Sierens (2007) developed another quasi-dimensional two-zone combustion model in which a laminar burning velocity correlation is combined with a number of turbulent burning velocity models to calculate the pressure and temperature development in hydrogen engines. The model gives insight into what influence fuel consumption rate. It was simulated and experimentally validated successfully, but it does not account for large spatial variations in temperature in the cylinder charge.

Bazari (1994) presented a non-linear transient engine cycle simulation software integrated into a two-dimensional multi-zone combustion-emissions model in order to predict exhaust emissions under transient operating conditions. They demonstrated using this combustion-emissions model the characteristics of engine transient operation. The model was validated satisfactorily, but it does not account for large spatial variations in mixture composition in the cylinder charge.

Reitz and Rutland (1992) modified a 3D computer code, KIVA, for the USA National Aeronautics and Space Administration (NASA) to include further developed sub-models for diesel engine flow and combustion which are: wall heat transfer model with unsteadiness and compressibility, Shell multistep kinetics and laminar-turbulent characteristic time combustion model with unburned HC and Zeldo'vich NOx, and spray/wall impingement model with rebounding, breaking-up, and sliding drops. The model was experimentally validated successfully. However, it is valid only for diesel engines.

Paul and Ganesan (2010) developed a 3D model of the direct injection diesel engine manifolds and of the cylinder using the pre-processor GAMBIT and using the CFD code STAR-CD, to investigate the effect of helical, spiral, and helical-spiral combination manifold configurations on air motion and turbulence inside the cylinder. This experimentally validated model demonstrated that helical-spiral manifold gives the maximum swirl ratio inside the cylinder but at the expense of reduced volumetric efficiency. This outcome gives insight into the fuel consumption efficiency in diesel engines since the fuel-to-air ratio in diesel engines is usually lean and thus the reduction in volumetric efficiency becomes insignificant. In addition, the swirl ratio is particularly helpful in improving the efficiency of fuel consumption in diesel engines.

Patterson et al. (1994) developed 3D KIVA code to study the effects of injection pressure and split injections on diesel engine performance and soot and NOx emissions. The KIVA code included the following sub-models: a wave breakup atomisation model, drop drag with drop distortion, spray/wall interaction with sliding, rebounding, and breaking-up drops, multistep kinetics ignition and laminar-turbulent characteristic time combustion, wall heat transfer with unsteadiness and compressibility, Zeldovich NOx formation, and soot formation with Nagle Strickland-Constable oxidation. Soot and NOx emissions were found to be very sensitive to factors that influence the chamber gas temperatures such as crevice flow.

Arsie et al. (2007) proposed a semi-empirical two-zone thermodynamic model to optimise the control parameters of high speed direct injection (HSDI) diesel engines. The model facilitates the engine control design for common rail diesel engines with multiple injections, where the large number of control parameters requires a large experimental tuning effort. Yet, it does not account for large spatial variations in mixture composition and temperature in the cylinder charge. An optimisation analysis based on the proposed model was then performed aiming at minimising NOx emissions with constraints on soot emissions and engine performance [e.g., indicated mean effective pressure (IMEP)]. The research findings of this study were supported by the research findings of Arsie et al. (2005, 2006).

Rakopoulos et al. (2003) presented a two-zone model for the evaluation of the closed cycle of a direct injection (DI) diesel engine. The cylinder contents sub-model comprised a non-burning zone of air, homogeneous zone in which fuel is continuously supplied, and soot formation zone. The model demonstrated satisfactory predictions, but it is valid only for diesel engines.

Roy and Liu (2008) presented a quasi-dimensional 3D model with eight degrees of freedom (DOF) to simulate and to animate the response of a vehicle to different road, traction, braking and wind conditions. The model was developed for vehicle suspension design and performance analysis. Its inputs are the engine throttle and starter, brake, transmission gear number, and clutch position. The model outputs are suspension parameters, such as rigidity and damping, and the longitudinal energy loss. Albeit the model was validated satisfactorily, it does not account for large spatial variations in mixture composition in the cylinder charge.

2.5.3 Multi-dimensional/multi-zone models

As the last subcategory of the number of dimensions-based modelling classification, multi-dimensional/multi-zone modelling is preferred when modelling accuracy is concerned. Many researchers adopt this type of modelling when they model the vehicle powertrain fuel consumption and emissions rates. Taklanti and Delhaye (1999) presented the methodologies of multi-dimensional modelling of the aerodynamic and combustion in Diesel engines developed at the PSA Peugeot Citroën. These methodologies are based on CFD and combustion simulation applications. Although the models developed using these methodologies are accurate and give insight into what influence the rate of fuel consumption in diesel engines, they require relatively long computational time and therefore are not suitable for control applications without being simplified.

Daw et al. (1998) proposed a low-dimensional, physically motivated, non-linear model for cyclic combustion variation in spark-ignited internal combustion engines. A key feature of the model is the interaction between stochastic, small-scale fluctuations in engine parameters and non-linear deterministic coupling between successive engine cycles. Albeit the model gives insight into what influence the rate of fuel consumption in internal combustion engines, it is valid only for spark-ignition engines.

Easley et al. (2001) developed single and multi-zone models of HCCI engines by coupling the first law of thermodynamics with detailed chemistry of hydrocarbon fuel oxidation and NOx formation. These models are intent to be used in parametric studies to determine the effect of heat loss, crevice volume, temperature stratification, fuel-air equivalence ratio, engine speed, and boosting on HCCI engine operation. Though the predictions that the models provide are satisfactorily accurate, their usually-included phenomenological sub-models result in having results that may vary according to the assumed initial or boundary conditions in these sub-models.

Aceves et al. (2000) developed a multi-zone model for prediction of the HCCI combustion and emissions and found that the hottest part of the mixture ignites first, and compresses the rest of the charge, which then ignites after a short-time lag. They found that turbulence has little effect on HCCI combustion. The model was validated satisfactorily, but it requires relatively long computational time.

Komninos et al. (2005) presented a multi-zone phenomenological model for simulating the mass exchange between zones and the flow of the in-cylinder mixture in and out of the crevice region in HCCI engines. That experimentally validated model describes the combustion, heat and mass transfer processes for the closed part of the engine cycle, i.e., compression, combustion and expansion, helping in better understanding what influence the rate of fuel consumption. The findings of that study are further supported by the findings of Komninos and Hountalas (2008). Though the model demonstrated satisfactory predictions, it has relatively low computational efficiency.

Havstad et al. (2010) described CHEMKIN-based multi-zone model that simulates the expected combustion variations in a single-cylinder engine fuelled with iso-octane as the engine transitions from spark ignited (SI) combustion to HCCI combustion. The model captures many of the important experimental trends, including stable SI combustion at low EGR (–10%), a transition to highly unstable combustion at intermediate EGR, and finally stable HCCI combustion at very high EGR (–75%). Albeit the model provides insight into what influence the rate of fuel consumption, the usually included phenomenological sub-models in such model result in having results that may vary according to the assumed initial or boundary conditions in these sub-models.

Kabir et al. (2010) investigated the Wiebe function as a multi-dimensional mathematical model of the combustion process in internal combustion engines. They showed that the computational time to determine the combustion parameters, which are the crank angle at the start of ignition, the total amount of heat release, and the combustion duration is too high to be used in the real-time operation using the Wiebe function.

3 Comparisons between the subcategories of each of the modelling classifications

In an endeavour to get a deeper insight into the subcategories of each of the modelling classifications presented herein we present in this section comparisons between these subcategories with respect to assumptions, limitations, merits, drawbacks, characteristic parameters, data collection technique, accuracy, and relevance to road traffic.

3.1 Comparison of assumptions and limitations in subcategories of modelling

In modelling, assumptions play a key role to tell how robust the developed model is. Modelling's limitations as well help the model users to grasp to what extent this model can be used effectively and help the model developers to better understand how this model can be extended and further developed. Thus, this section elucidates the key assumptions and limitations in the scale of the input variable-based modelling classification, in the formulation approach-based modelling classification, in the main input variable-based modelling classification, in the state variable value-based modelling classification, and in the number of dimensions-based modelling classification as shown in Table 1, Table 2, Table 3, Table 4, and Table 5, respectively.

3.2 Comparison of merits and drawbacks of subcategories of modelling

Since modelling types vary with respect to strengths and weaknesses, this section presents how different the presented modelling subcategories are with respect to these aspects. Thus, the merits and drawbacks of the scale of the input variable-based modelling classification, of the formulation approach-based modelling classification, of the main input variable-based modelling classification, of the state variable value-based modelling classification, and of the number of dimensions-based modelling classification are presented in Table 6, Table 7, Table 8, Table 9, and Table 10, respectively.

3.3 Comparison of characteristic parameters and data collection technique in subcategories of modelling

Characteristic parameters are key to implement models. They reflect the inputs to and deliverables of the model. The technique of data collection is crucial as well in making the models developed using these data valid. Therefore, the characteristic parameters of and data collection technique in the scale of the input variables-based modelling classification, in the formulation approach-based modelling classification, in the main input variable-based modelling classification, in the state variable value-based modelling classification, and in the number of dimensions-based modelling classification are elucidated in this section as shown in Table 11, Table 12, Table 13, Table 14, and Table 15, respectively.

Table 1 The main assumptions and limitations in the scale of the input variable-based modelling classification

Modelling type	*Assumptions*	*Limitations*
Microscopic vehicle fuel consumption and emissions models	1 Assuming a constant emissions rate (Rakha and Ahn, 2004).	1 Relatively expensive and time-consuming (Yue, 2008; Rakha et al., 2011) 2 The requirements of a validated microscopic model for large-scale modelling are: a the model must be capable of modelling origin-destination demand tables b the model must be capable of modelling dynamic traffic routing c the model must be capable of modelling the dynamic interaction of freeway/arterial facilities (Rakha et al., 1998).
Macroscopic vehicle fuel consumption and emissions models	1 Assuming all vehicles maintain a constant speed while on the highway and no overtaking is allowed (Durrani et al., 2010). Vehicles follow each other with the same speed. If a vehicle is below the desired speed it will accelerate to that speed using the maximum possible acceleration for the given speed and vehicle type. 2 All vehicles pollute similarly for the same average speed and vehicle-miles travelled (An and Barth, 1997). 3 Variations in driver behaviour can be neglected (An and Barth, 1997).	1 Are based on statistical analysis of publicly available data and engine maps (Yue, 2008; Rakha et al., 2011). 2 Do not adequately take into account aerodynamic drag resistance at high speeds, and thus they should only be used for average speeds of less than 55 km/h in most cases (Akcelik, 1985).
Mesoscopic vehicle fuel consumption and emissions models	1 Assuming a constant emissions rate (Rakha and Ahn, 2004).	1 Relatively expensive and time-consuming (Yue, 2008; Rakha et al., 2011).

Table 2 The main assumptions and limitations in the formulation approach-based modelling classification

Modelling type		*Assumptions*		*Limitations*
Analytical models	1	Fuel consumption rates for diesel and gasoline vehicles, such as passenger cars and diesel buses, are determined by vehicle specific power (VSP), engine speed, engine displacement volume, vehicle mass (Frey et al., 2007)	1	Since they usually are not simple models, they can not be easily integrated into modern automobile control systems without simplification which in turn may lead to modelling errors (Organisation for Economic Co-operation and Development, 2002).
	2	A constant inlet manifold temperature (Heywood, 1988; Bohn et al., 2006; De Nicolao et al., 1996)		
	3	Each cylinder undergoes the same thermodynamic cycle (Streit and Borman, 1971)		
	4	The intake manifold pressure is constant (Streit and Borman, 1971)		
	5	Steady flow is assumed in the compressor of the turbocharger (Streit and Borman, 1971)		
	6	Volumetric efficiency is assumed to be constant (Souder, 2002)		
	7	Uniform distribution of pressure, composition and temperature in the intake and exhaust manifolds (Sun et al., 2005)		
	8	The ideal gas law applies in the intake manifold, engine, and exhaust manifold (Sun et al., 2005)		
	9	The combustion process is stoichiometric (Ni and Henclewood, 2008; Karmiggelt, 1998)		
	10	Quasi-steady, adiabatic, one dimensional flow equations are used to predict mass flows past the intake and exhaust valves (Kim et al., 2002)		
	11	Combustion is modelled as a uniformly distributed heat release process (Kim et al., 2002)		
	12	Constant temperature of exhaust manifold (Ceccarelli et al., 2009)		
	13	Mass moments of inertia of the engine's components at low engine speeds are constant (Shiao et al., 1994)		
	14	Air is an ideal gas (Ni and Henclewood, 2008)		

Table 2 The main assumptions and limitations in the formulation approach-based modelling classification (continued)

Modelling type		*Assumptions*		*Limitations*
Empirical models	1	Emission rates can be approximated as a linear function of fuel rate (Cappiello et al., 2002)	1	Simplification of a model leads to some modelling errors (Organisation for Economic Co-operation and Development, 2002)
	2	The variables that govern emission rates are the same variables that govern fuel rate (Cappiello et al., 2002)		
	3	No slip occurs either at the tire road interface or across the vehicle's torque converter [a reasonable assumption for gradual manoeuvres' at highway speeds (McMahon et al., 1990; Gerdes and Hedriek, 1997)]	2	They sometimes do not describe the physical phenomena associated with vehicle operation and emissions productions comprehensively with explainable mathematical trends and rationally-accepted results (Ni and Henclewood, 2008; Hendricks, 1986; Cook et al., 2006; Barth et al., 1996, 1998; Ahn, 1998)
	4	The ideal gas law holds in the intake manifold (Gerdes and Hedriek, 1997)		
	5	The engine is adiabatic (Assanis and Heywood, 1986)	3	In evaluating fuel consumption and exhaust emissions models, vehicle-to-vehicle correlation is impossible due to the well-known high variability of emissions between nominally identical vehicles (Leung and Williams, 2000)
	6	In a multi-cylinder reciprocator diesel model, each cylinder undergoes the same thermodynamic cycle (Assanis and Heywood, 1986)		
	7	The fluid in all parts of the engine obeys ideal gas law and Dalton's law of non-reacting mixtures (McMahon et al., 1990)		
	8	Uniformity of temperature and pressure (McMahon et al., 1990)		
Statistical models	1	Assuming the data are a representative sample of the facility's traffic (Rothery, 1975)	1	Available data are often not sufficiently detailed (in terms of key variables such as hourly traffic, freight vehicle shares, fuel consumption per vehicle, average annual distance travelled) (Organisation for Economic Co-operation and Development, 2002)
	2	Average vehicle fuel efficiency (Ang, 1990)		
	3	Average driver behaviour (Ang, 1990)		
	4	Average trip characteristics (Ang, 1990)	2	Although emission maps are relatively easy to be generated and to be used, emission maps are sometimes not satisfactory because emission maps can be highly sensitive to the driving cycle (Cappiello et al., 2002)
			3	Emission maps are also sparse and not flexible enough to account for such factors as road grade, loading condition such as accessory use, or history effects (Cappiello et al., 2002)
Graphical models	1	The processor is sufficiently fast to run the model (Weeks and Moskwa, 1995)	1	Generate estimates of relatively low prediction accuracy (Smit and McBroom, 2009)
	2	Air and EGR are homogeneously mixed and have the same molecular weight and temperature (Weeks and Moskwa, 1995)		

Table 3 The main assumptions and limitations in the main input variable-based modelling classification

Modelling type		*Assumptions*		*Limitations*
Average speed models	1	Assuming all vehicles maintain a constant speed while on the highway and no overtaking is allowed (Durrani et al., 2010). Vehicles follow each other with the same speed. If a vehicle is below the desired speed it will accelerate to that speed using the maximum possible acceleration for the given speed and vehicle type.	1	Should only be used for average speeds of less than 55 km/h in most cases (Akcelik, 1985)
	2	All vehicles pollute similarly for the same average speed and vehicle-miles travelled (An and Barth, 1997).	2	Are based on statistical analysis of publicly available data and engine maps (Rakha et al., 2011).
	3	Variations in driver behaviour can be neglected (An and Barth, 1997).		
Instantaneous speed models	1	A stimulus-response relationship exists that describes the control process of a driver-vehicle unit (Rothery, 1975).	1	Relatively expensive and time-consuming (Rakha et al., 2011).
	2	Vehicles are not operating under cold start conditions (Park et al., 2001).		
	3	Vehicles follow each other with the same speed (Park et al., 2001).		
	4	Constant reaction delay time for all drivers (Xin et al., 2008).		
Specific power models	1	Most alternative fuelled vehicles were assumed to have the same corrections as their gasoline counterparts (Davis, 2005).	1	The use of vehicle specific power usually results in a bang-bang control (i.e., the optimum fuel consumption results from a full throttle acceleration) (Durrani et al., 2010).

Table 4 The main assumptions and limitations in the state variable value-based modelling classification

Modelling type		*Assumptions*		*Limitations*
Crank-angle resolution-based models	1	A constant intercooler temperature (Guzzella and Amstutz, 1998)	1	Require relatively long computational time for their complexity (Guzzella and Amstutz, 1998)
	2	The engine is assumed to be nominally operated at the constant set-point (e.g., angular speed, mass flow rate, and temperature) (Guzzella and Amstutz, 1998)		
Mean value-based models	1	All cylinders and all strokes have the same crank-angle phase difference (Guzzella and Amstutz, 1998)	1	Do not account for delays (Guzzella and Amstutz, 1998)
	2	The intake manifold and cylinders are modelled as mass and internal energy reservoirs in the usual 'emptying and filling' approach (Winterbone et al., 1977)		
	3	The specific heats of air at constant pressure and constant volume can be assumed constant and equal for both air and exhaust-gas (Guzzella and Amstutz, 1998)		
	4	The engine has infinitely many infinitesimally small cylinders (Guzzella and Amstutz, 1998)		

Table 5 The main assumptions and limitations in the number of dimensions-based modelling classification

Modelling type		*Assumptions*		*Limitations*
Zero/one dimensional/single zone models	1	The cylinder charge is uniform in both composition and temperature, at all time during the cycle (Jung and Assanis, 2001; Foster, 1985).	1	Do not account for the spatial variation in mixture composition and temperature in the cylinder charge (Jung and Assanis, 2001; Foster, 1985).
Quasi dimensional models	1	There is a degree of spatial variation in mixture composition and temperature in the cylinder charge (Jung and Assanis, 2001; Austen and Lyn, 1961).	1	Do not account for large spatial variations in mixture composition and temperature in the cylinder charge (Jung and Assanis, 2001; Austen and Lyn, 1961).
Multi dimensional/multi zone models	1	There is spatial variation in mixture composition and temperature in the cylinder charge (Jung and Assanis, 2001; Bracco, 1985)	1	Require relatively long computational time and therefore are less suitable for control applications (Jung and Assanis, 2001; Bracco, 1985).
	2	The control volume of each zone is treated as an open system, and mass and energy equations are solved for each zone (Jung and Assanis, 2001; Bracco, 1985).		

Table 6 The merits and drawbacks of the scale of the input variable-based modelling classification

Modelling type		*Merits*		*Drawbacks*
Microscopic vehicle fuel consumption and emissions models	1	Capture transient changes in a vehicle's speed and acceleration level as it travels on a highway network (Marsden et al., 2001).	1	The calibration of a microscopic model of a large-scale network is an extensively time consuming task (Rakha et al., 1998).
	2	Capture the impact of intelligent transportation system strategies such as traffic signal coordination (Marsden et al., 2001; Fang and Elefteriadou, 2008).	2	Microscopic models are very labour intensive in conducting inventory analysis given that they need very detailed information which may not be available (Yue, 2008).
	3	More accurate in estimating vehicle emissions than macroscopic models in terms of both their absolute magnitude and their relative trends than of average speed-based models (Hallmark et al., 2000; Rakha and Van Aerde, 2000; Fang and Elefteriadou, 2008).		
Macroscopic vehicle fuel consumption and emissions models	1	Are helpful in estimating aggregate emissions inventories (Rakha and Ahn, 2004; Gning, 2011).	1	Ignore transient changes in a vehicle's speed and acceleration level as it travels on a highway network (Yue, 2008).
			2	Ignore the impact of intelligent transportation system strategies such as traffic signal coordination (Rakha and Van Aerde, 2000).
			3	Less accurate in estimating vehicle emissions than microscopic models (Hallmark et al., 2000).
			4	Do not include congestion algorithms (Smit et al., 2008).
			5	Do not adequately take into account aerodynamic drag resistance at high speeds (Akcelik, 1985).
Mesoscopic vehicle fuel consumption and emissions models	1	Mesoscopic models utilise link-by-link input parameters to construct a synthetic drive cycle and to compute average link fuel consumption and emission rates while utilising instantaneous speed and instantaneous acceleration inputs (Yue, 2008; Li and Ioannou, 2004).	1	Can not be used alone to estimate emissions inventory (Yue, 2008).
	2	Can be used for computing average fuel consumption and emission rates for a specific facility type (Yue, 2008; An and Barth, 1997).		

Table 7 The merits and drawbacks of the formulation approach-based modelling classification

Modelling type		*Merits*		*Drawbacks*
Analytical models	1	Describe the physical phenomena associated with vehicle operation and emissions productions comprehensively and with explainable mathematical trends (Barth et al., 1996, 1998; Ahn, 1998).	1	More calculation intensive which may result in reducing software efficiency in case of implementation (Lindhjem eta l., 2004).
	2	Result in reasonable and rationally-accepted results (Barth et al., 1996, 1998; Ahn, 1998).	2	The model may be more complicated and thus require additional training for users in case of implementation (Lindhjem et al., 2004).
	3	Most accurate type of formulation approach-based modelling (Hendricks, 1986; Ni and Henclewood, 2008).		
Empirical models	1	Simple model that can be easily integrated into vehicle control systems (Lindhjem et al., 2004).	1	A lot of experimental/field data must be taken (Lindhjem et al., 2004).
			2	They are valid only for the range of data based on which they are built (Lindhjem et al., 2004).
			3	They sometimes do not describe the physical phenomena associated with vehicle operation and emissions productions comprehensively with explainable mathematical trends and rationally-accepted results (Ni and Henclewood, 2008; Hendricks, 1986; Cook et al., 2006; Barth et al., 1996, 1998; Ahn, 1998).
Statistical models	1	Relatively easy to be made (Lindhjem et al., 2004).	1	Data-driven and thus their prediction can be relatively inaccurate (Lindhjem et al., 2004).
	2	Uncertainty can be quantified (Lindhjem et al., 2004).		
			2	Require recalibration with each dataset (Lindhjem et al., 2004).
			3	Difficult to interpolate gaps in the dataset and to extrapolate data beyond the bounds of the dataset (Lindhjem et al., 2004).
			4	Less accurate type of formulation approach-based modelling than empirical models (Lloyd and Rudd, 2007).
			5	Take relatively long simulation times and needs relatively large memory requirements (Nieuwoudt et al., 2006).
Graphical models	1	Easy to be recognised and understood visually (Al-qaimari et al., 1995; Autili and Pelliccione, 2008).	1	Least accurate type of formulation approach-based modelling (Lloyd and Rudd, 2007).

Table 8 The merits and drawbacks of the main input variable-based modelling classification

Modelling type		*Merits*		*Drawbacks*
Average speed models	1	Are helpful in estimating aggregate emissions inventories (Rakha and Ahn, 2004; Gning et al., 2011).	1	Ignore transient changes in a vehicle's speed and acceleration level as it travels on a highway network (Yue, 2008)
			2	Fail to capture the impact of intelligent transportation system strategies such as traffic signal coordination (Rakha and Van Aerde, 2000)
			3	Less accurate in estimating vehicle emissions than instantaneous speed models (Hallmark et al., 2000)
			4	Do not include congestion algorithms (Smit et al., 2008)
			5	Do not adequately take into account aerodynamic drag resistance at high speeds (Akcelik, 1985).
Instantaneous speed models	1	Capture transient changes in a vehicle's speed and acceleration level as it travels on a highway network (Marsden et al., 2001)	1	Are labour intensive in conducting inventory analysis given that they need very detailed information which may not be available (Yue, 2008).
	2	Capture the impact of intelligent transportation system strategies such as traffic signal coordination (Marsden et al., 2001)		
	3	More accurate in estimating vehicle emissions than average speed models in terms of both their absolute magnitude and their relative trends than of average speed-based models (Hallmark et al., 2000; Rakha and Van Aerde, 2000).		
Specific power models	1	More suitable for heavy duty diesel vehicle engines and more accurate than average speed models (Feng, 2007).	1	Need availability of relevant specific power data (Frey et al., 2007).

Table 9 The merits and drawbacks of the state variable value-based modelling classification

Modelling type		*Merits*		*Drawbacks*
Crank-angle resolution-based models	1	Accurate (Guzzella and Amstutz, 1998)	1	Require relatively long computational time for their complexity (Guzzella and Amstutz, 1998)
Mean value-based models	1	Less complicated than Crank-angle resolution-based models and thus require only short computational time (Guzzella and Amstutz, 1998; Eriksson et al., 2002)	1	Less accurate than the crank-angle resolution-based models (Guzzella and Amstutz, 1998; Eriksson et al., 2002)
	2	Convenient for control applications (Guzzella and Amstutz, 1998; Eriksson et al., 2002)		

Table 10 The merits and drawbacks of the number of dimensions-based modelling classification

Modelling type		*Merits*		*Drawbacks*
Zero/one dimensional/single zone models	1	Simplicity (Killingsworth et al., 2006; Jung and Assanis, 2001)	1	Low accuracy (Jung and Assanis, 2001)
	2	High computational efficiency (Killingsworth et al., 2006; Jung and Assanis, 2001)		
	3	Convenient for modelling and powertrain control applications (Jung and Assanis, 2001)		
Quasi dimensional models	1	Moderate accuracy (Jung and Assanis, 2001)	1	Are not suitable for modelling large spatial variation in mixture composition and temperature in the cylinder charge (Jung and Assanis, 2001)
	2	Require a moderate amount of computational time (Jung and Assanis, 2001)		
Multi dimensional/multi zone models	1	High accuracy (Jung and Assanis, 2001)	1	Require relatively long computational time (Jung and Assanis, 2001)
			2	Their usually included phenomenological sub-models result in having results that may vary according to the assumed initial or boundary conditions in these sub-models (Jung and Assanis, 2001)

Table 11 The characteristic parameters of and data collection technique in the scale of the input variable-based modelling classification

Modelling type		*Characteristic parameters*		*Data collection technique*
Microscopic vehicle fuel consumption and emissions models	1	Instantaneous crankshaft speed (Rakha and Van Aerde, 2000; Ahn, 2002; De Nicolao et al., 1996; Rakha et al., 2011)	1	Field data collection (Yildiz et al., 2009; Sorenson et al., 2005)
	2	Instantaneous crankshaft acceleration (Rakha and Van Aerde, 2000; Ahn, 2002; De Nicolao et al., 1996; Rakha et al., 2011)	2	Lab dynamometer (Yildiz et al., 2009; Sorenson et al., 2005)
Macroscopic vehicle fuel consumption and emissions models	1	Vehicle's average speed (Rakha et al., 2011)	1	Field data collection (Rakha et al., 2011; Rakha and Ahn, 2004)
	2	Vehicle's average acceleration (Rakha et al., 2011)	2	Engine maps (Rakha et al., 2011; Rakha and Ahn, 2004)
Mesoscopic vehicle fuel consumption and emissions models	1	Instantaneous engine speed (De Nicolao et al., 1996; Yue, 2008; Rakha and Van Aerde, 2000; Ahn, 2002)	1	Field data collection (Rakha et al., 2011; Rakha and Ahn, 2004; Yue, 2008)
	2	Instantaneous engine acceleration (Yue, 2008; Rakha and Van Aerde, 2000; Ahn, 2002)	2	Engine maps (Rakha et al., 2011; Rakha and Ahn, 2004; Yue, 2008)

Table 12 The characteristic parameters of and data collection technique in the formulation approach-based modelling classification

Modelling type		*Characteristic parameters*		*Data collection technique*
Analytical models	1	Instantaneous crankshaft speed (Rakha and Van Aerde, 2000; Ahn, 2002; De Nicolao et al., 1996; Rakha et al., 2011)		No data are required to be collected.
	2	Instantaneous crankshaft acceleration (Rakha and Van Aerde, 2000; Ahn, 2002; De Nicolao et al., 1996; Rakha et al., 2011)		
	3	Engine torque (De Nicolao et al., 1996; Rakha et al., 2011)		
	4	Intake manifold pressure (De Nicolao et al., 1996; Rakha et al., 2011)		
	5	Engine displacement volume (Frey et al., 2007)		
Empirical models	1	Vehicle's average speed (Rakha et al., 2011)	1	Field data collection (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)
	2	Vehicle's average acceleration (Rakha et al., 2011)		
	3	Engine torque (De Nicolao et al., 1996; Rakha et al., 2011)	2	Engine maps (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999).
Statistical models	1	Vehicle's average speed (Rakha et al., 2011)	1	Remote sensing-based field data collection with the aid of global positioning system (GPS) in case of expected high emission rates (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999; Lindhjem et al., 2004)
	2	Vehicle's average acceleration (Rakha et al, 2011)		
	3	Engine torque (De Nicolao et al., 1996; Rakha et al., 2011)	2	On-vehicle portable dynamometer with on-vehicle data-processing unit-based field data collection in case of expected low emission rates (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999; Lindhjem et al., 2004)
	4	Road grade (Lindhjem et al., 2004)		
	5	Vehicle weight (Lindhjem et al., 2004)		
	6	Loading condition, such as accessory use (e.g., air conditioning) (Yue, 2008)	3	Engine maps (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)
Graphical models	1	Vehicle's average speed (Rakha et al., 2011)	1	Field data collection (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)
	2	Vehicle's average acceleration (Rakha et al., 2011)		
			2	Engine maps (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)

Table 13 The characteristic parameters of and data collection technique in the main input variable-based modelling classification

Modelling type		*Characteristic parameters*		*Data collection technique*
Average speed models	1	Vehicle's average speed (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)	1	Field data collection (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)
	2	Vehicle's average acceleration (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)	2	Engine maps (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)
Instantaneous speed models	1	Crankshaft instantaneous speed (De Nicolao et al., 1996; Joumard et al., 1999; Rakha and Van Aerde, 2000; Ahn, 2002)	1	Field data collection (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)
	2	Crankshaft instantaneous acceleration (De Nicolao et al., 1996; Joumard et al., 1999; Rakha and Van Aerde, 2000; Ahn, 2002)	2	Lab dynamometer (Rakha et al., 2011; Rakha and Ahn, 2004; Joumard et al., 1999)
Specific power models	1	Engine torque (De Nicolao et al., 1996; Rakha et al., 2011)	1	Field data collection (Rakha et al., 2011; Rakha and Ahn, 2004)
	2	Crankshaft speed (De Nicolao et al., 1996; Rakha et al., 2011)		
	3	Intake manifold pressure (De Nicolao et al., 1996; Rakha et al., 2011)	2	Engine maps (Rakha et al., 2011; Rakha and Ahn, 2004)
	4	Engine displacement volume (Frey et al., 2007)	3	Portable emissions measurement instrument (Wang et al., 2008)

Table 14 The characteristic parameters of and data collection technique in the state variable value-based modelling classification

Modelling type		*Characteristic parameters*		*Data collection technique*
Crank-angle resolution-based models	1	Crank angle (Guzzella and Amstutz, 1998)	1	For models' validation, published data of real engines are used, such as manufacturer's turbine data sheets (Guzzella and Amstutz, 1998)
	2	Crank shaft angular speed (Guzzella and Amstutz, 1998)		
	3	Fluid mass flow rate (Guzzella and Amstutz, 1998)	2	For models' validation, measured data from real engines are used (Guzzella and Amstutz, 1998)
	4	Fluid temperature (Guzzella and Amstutz, 1998)		
Mean value-based models	1	Intake manifold temperature (Guzzella and Amstutz, 1998; Eriksson et al., 2002)	1	For models' validation, published data of real engines are used, such as manufacturer's turbine data sheets (Guzzella and Amstutz, 1998; Eriksson et al., 2002)
	2	Intake manifold pressure (Guzzella and Amstutz, 1998; Eriksson et al., 2002)		
	3	Exhaust manifold temperature (Guzzella and Amstutz, 1998; Eriksson et al., 2002)		
	4	Exhaust manifold pressure (Guzzella and Amstutz, 1998; Eriksson et al., 2002)	2	For models' validation, measured data from real engines are used (Guzzella and Amstutz, 1998; Eriksson et al., 2002)
	5	Fluid mass flow rate (Guzzella and Amstutz, 1998; Eriksson et al., 2002)	3	For developing empirical mean value-based models, published data of real engines or measured data from real engines are used (Guzzella and Amstutz, 1998; Eriksson et al., 2002)

Table 15 The characteristic parameters of and data collection technique in the number of dimensions-based modelling classification

Modelling type		*Characteristic parameters*		*Data collection technique*
Zero/one dimensional/single zone models	1	Temperature of the zone (Jung and Assanis, 2001; Foster, 1985)	1	Data for validation are experimental data collected from representative engines (Jung and Assanis, 2001; Foster, 1985)
	2	Volume of the zone (Jung and Assanis, 2001; Foster, 1985)		
Quasi dimensional models	1	Temperature of the zone (Jung and Assanis, 2001; Austen and Lyn, 1961)	1	Data for validation are experimental data collected from representative engines (Jung and Assanis, 2001; Austen and Lyn, 1961)
	2	Volume of the zone (Jung and Assanis, 2001; Austen and Lyn, 1961)		
Multi dimensional/multi zone models	1	Start of injection timing (Jung and Assanis, 2001; Bracco, 1985)	1	Data for validation are experimental data collected from representative engines (Jung and Assanis, 2001; Bracco, 1985)
	2	Injection pressure (Jung and Assanis, 2001; Bracco, 1985)		
	3	Density of the mixture (Jung and Assanis, 2001; Bracco, 1985)		
	4	The mass fraction of fuel vapour (Jung and Assanis, 2001; Bracco, 1985)		
	5	The mass fraction of oxygen (Jung and Assanis, 2001; Bracco, 1985)		
	6	Temperature of the zone (Jung and Assanis, 2001; Bracco, 1985)		
	7	Volume of the zone (Jung and Assanis, 2001; Bracco, 1985)		
	8	Engine average speed (Jung and Assanis, 2001; Bracco, 1985)		
	9	Average fuel/air equivalence ratio (Jung and Assanis, 2001; Bracco, 1985)		
	10	Exhaust back pressure (Jung and Assanis, 2001; Bracco, 1985)		

3.4 Comparison of accuracy and relevance to road traffic in subcategories of modelling

Models vary in terms of accuracy. They vary as well in their relevance to transportation applications. This section identifies how accurate and how relevant to transportation applications is each subcategory in the presented modelling classifications. Table 16, Table 17, Table 18, Table 19, and Table 20, illustrate the accuracy and relevance to road traffic of the scale of the input variable-based modelling classification, of the formulation approach-based modelling classification, of the main input variable-based modelling classification, of the state variable value-based modelling classification, and of the number of dimensions-based modelling classification, respectively.

Table 16 The accuracy and relevance to road traffic in the scale of the input variable-based modelling classification

Modelling type		*Accuracy*		*Relevance to road traffic*
Microscopic vehicle fuel consumption and emissions models	1	Relatively accurate (Ding, 2000; Hallmark et al., 2000)	1	High (Yue, 2008)
Macroscopic vehicle fuel consumption and emissions models	1	Less accurate than microscopic models (Ding, 2000; Hallmark et al., 2000)	1	Low (Yue, 2008)
Mesoscopic vehicle fuel consumption and emissions models	1	More accurate than macroscopic models (Yue, 2008)	1	Moderate (Yue, 2008)

Table 17 The accuracy and relevance to road traffic in the scale of the formulation approach-based modelling classification

Modelling type		*Accuracy*		*Relevance to road traffic*
Analytical models	1	Most accurate type of formulation approach-based modelling (Ni and Henclewood, 2008; Hendricks, 1986)	1	High (Hellström, 2010; Biteus, 2002; Hendricks, 1997; Silverlind, 2001; Karmiggelt, 1998)
Empirical models	1	Less accurate than analytical models (Nieuwoudt et al., 2006; Karmiggelt, 1998)	1	High (Rakha and Ahn, 2004)
Statistical models	1	Less accurate than empirical models (Nieuwoudt et al., 2006; Karmiggelt, 1998)	1	High (Rakha and Ahn, 2004)
Graphical models	1	Least accurate type of formulation approach-based modelling since they are simplification based on analytical models (Nieuwoudt et al., 2006; Karmiggelt, 1998)	1	Moderate (Cho and Hedrick, 1989; Grossi et al., 2009)

Table 18 The accuracy and relevance to road traffic in the main input variable-based modelling classification

Modelling type		*Accuracy*		*Relevance to road traffic*
Average speed models	1	Were validated against field data with modelling errors reach 57% (Joumard et al., 1999)	1	High (Yue, 2008; Esteves-Booth et al., 2002)
	2	The use of average speed as a sole explanatory variable is inadequate for estimating vehicle fuel consumption and emissions, and the addition of speed variability as an explanatory variable results in better models (Ding, 2000)		
Instantaneous speed models	1	Were validated against field data and lab dynamometer test data with modelling errors reach 57% (Joumard et al., 1999)	1	Moderate (Yue, 2008; Esteves-Booth et al., 2002)
	2	More accurate in estimating vehicle emissions than average speed models (Hallmark et al., 2000)		
Specific power models	1	Were validated against field data with modelling errors reach 57% (Joumard et al., 1999)	1	Moderate (Rakha et al., 2011)

Table 19 The accuracy and relevance to road traffic in the state variable value-based modelling classification

Modelling type		*Accuracy*		*Relevance to road traffic*
Crank-angle resolution-based models	1	High (Guzzella and Amstutz, 1998)	1	Moderate (Guzzella and Amstutz, 1998)
Mean value-based models	1	Moderate (Guzzella and Amstutz, 1998; Eriksson et al., 2002)	1	High (Guzzella and Amstutz, 1998; Eriksson et al., 2002)

Table 20 The accuracy and relevance to road traffic in the number of dimensions-based modelling classification

Modelling type		*Accuracy*		*Relevance to road traffic*
Zero/one dimensional/single zone models	1	Low (Jung and Assanis, 2001; Foster, 1985)	1	High (Jung and Assanis, 2001; Foster, 1985)
Quasi dimensional models	1	Moderate (Jung and Assanis, 2001; Austen and Lyn, 1961)	1	Moderate (Jung and Assanis, 2001; Austen and Lyn, 1961)
Multi-dimensional/ multi-zone models	1	High (Jung and Assanis, 2001; Bracco, 1985)	1	Moderate (Jung and Assanis, 2001; Bracco, 1985)

4 Discussion

Modelling of vehicle fuel consumption and emissions emerged as an effective tool to help in developing and assessing vehicle technologies as well as to predict and to estimate aggregate vehicle fuel consumption and emissions. This study has reviewed the relevant literature review to identify the current state-of-the-art on vehicle fuel consumption and emissions modelling. The study has found that there are five types of modelling based on which the literature on vehicle fuel consumption and emissions can be categorised:

1 scale of the input variable-based modelling type, which was suggested by Yue (2008)

2 formulation approach-based modelling type

3 main input variable-based modelling type

4 state variable value-based modelling type, which was suggested by Guzzella and Amstutz (1998)

5 number of dimensions-based modelling type, which was suggested by Jung and Assanis (2001).

The relevant main models in each of these categories to vehicle's fuel consumption and emissions have been presented in this study.

The scale of the input variable-based modelling classification has been reviewed and its three subcategories have been explored which are microscopic, macroscopic, and mesoscopic models. The study has covered the relevant key models in the microscopic modelling subcategory which include CMEM, VT-Micro, Versit, PHEM, VeTESS, NetSim, EMIT, MOVES. The study has addressed as well the main packages of microscopic traffic simulation software which include PARAMICS, INTEGRATION, AIMSUN, VISSIM, and CORSIM. In the macroscopic models, the key models covered include MOBILE, EMFAC, Watson model, and COPERT. The study has addressed as well the main packages of macroscopic traffic simulation software which include TRANSIMS and CORFLO. The study has covered as well the key models in the mesoscopic models subcategory which include the elemental model, and MEASURE model. The study has addressed as well the main packages of mesoscopic traffic simulation software which include CONTRAM and SIDRA INTERSECTION.

The four subcategories in the formulation approach-based modelling classification have been reviewed as well which are analytical, empirical, statistical, and graphical modelling. The study has covered the main models in the analytical modelling subcategory which include the AMFC, and Bernoulli model. The study has covered as well the seminal models in the empirical modelling subcategory which include non-linear model of an internal combustion engines, non-linear model of an internal combustion engines, non-linear model of internal combustion engines, non-linear engine dynamic model, Assanis and Heywood's (1986) semi-empirical, thermodynamic and steady state turbocharged diesel engine model, comprehensive simulation model of Detroit Diesel Allison heavy duty diesel engines, Watson et al.'s (1980) empirical turbocharged diesel engine's combustion process model, friction losses in diesel engines model, TCS model, PERE model, the non-linear CLF, polynomial model, and Genta's (2003) parabolic model. In the statistical modelling subcategory the seminal models covered include non-linear neural network-based model for engine torque estimation, model of cyclic combustion variations in spark-ignited engines, universal model of internal combustion engines efficiency, and Kalman filter model. The graphical models subcategory has been covered as well in this study and the main models in this subcategory have been addressed which include V-Elph, POG, Modelica, bond graphs, and Dymola.

In the main input variable-based modelling classification, the three subcategories in this classification have been reviewed as well which are average speed, instantaneous speed, and specific power models. The study has covered the main models in the average speed models subcategory and identified the seminal models among them which include IMULATE, AFCM, TEXAS, and the disaggregate SCF model. The main models in the instantaneous speed models subcategory have been covered as well which include the INTEGRATION model. In the specific power models subcategory, the study has covered the main models in this subcategory as well which include HICE and HDDV-MEM models.

The overview has presented as well the two subcategories in the state variable value-based modelling classification which are crank-angle resolution-based models and mean value-based models. In the crank-angle resolution-based modelling subcategory, the main models have been covered which include the cylinder-by-cylinder model and the modified auto ignition KIM. The seminal value-based models have been covered as well which include MVEM large turbocharged two-stroke diesel engines, dynamic simulation model of SI engine subsystems, adiabatic mean value model of internal combustion engines, non-linear DYNAMO of a port fuel-injected engine, the mean flame speed model, the kernel initiation model, the entertainment and burn-up flame model, the flame sheet model, the laminar flame speed model, and the turbulent flame speed model.

The three subcategories in the number of dimensions-based modelling classification have been reviewed which are zero/one dimensional/single zone, quasi dimensional, and multi-dimensional/multi-zone modelling. The main zero/one dimensional/single zone models have been presented which include zero-dimensional compression and expansion model, modified version of Tanaka's reduced chemical kinetic model, the rate kinetic model, 1-D-KIVA 3v-GA, Polytropic model for compression ratio estimation, and Levenberg-Marquardt and standard model for compression ratio estimation. The quasi dimensional models have been covered as well and the main quasi dimensional models have been presented which include quasi-dimensional direct injection (DI) diesel combustion model, NASA's modified 3D KIVA computer code, the RNG k-ε turbulent model, NOx and soot exhaust emissions model, and quasi-dimensional transient spray combustion model. The last subcategory in the number of dimensions-based modelling classification presented in this study which is the multi-dimensional/multi-zone models has been explored as well and the main models in this subcategory have been presented which include the PSA Peugeot Citroën Multi-Dimensional Model, CHEMKIN-based multi-zone model, and multi-zone combustion model.

The analysis of vehicle fuel consumption and emission rates based on modelling indicated that vehicle fuel consumption and emission rates increase considerably as the number of vehicle stops increases especially at high cruise speed. The fidelity of these findings is supported by the research result that the trends of vehicle fuel consumption and emissions provided by current models are generally satisfactorily close to field data trends. The study has found that the main input variables and parameters for vehicle fuel consumption and emissions modelling are vehicle's average speed, vehicle's average acceleration, crankshaft's instantaneous speed, crankshaft's instantaneous acceleration, and engine specific power. In addition, the study has identified the other input variables and parameters for vehicle fuel consumption and emissions modelling which include engine torque, intake manifold pressure, engine displacement volume, road grade, vehicle weight, and loading condition such as accessory use. These vehicle fuel consumption and emissions models have been then compared with regard to assumptions, limitations, merits, drawbacks, accuracy, relevance to road traffic, and data collection technique.

As to the scale of the input variable-based modelling type, it has been found that microscopic vehicle fuel consumption and emissions models can capture transient changes in a vehicle's speed and acceleration level as it travels on a highway network, can capture the impact of ITS strategies such as traffic signal coordination, and are more accurate in estimating vehicle fuel consumption and emissions than macroscopic models in terms of both their absolute magnitude and their relative trends than of average speed-based models. In addition, macroscopic vehicle fuel consumption and emissions models have been found highly relevant to road traffic and most helpful in estimating aggregate emissions inventories.

It has been found that analytical modelling is the most accurate type of vehicle fuel consumption and emissions modelling and graphical modelling is the least accurate type of vehicle fuel consumption and emissions modelling in the formulation approach-based modelling type. In addition, it has been found that analytical models can describe the physical phenomena associated with vehicle operation and emissions productions comprehensively and with explainable mathematical trends, and result in reasonable and rationally-accepted results. It has been found as well that empirical models strike a balance between modelling accuracy and computational time effectiveness. Although Statistical models have been found requiring recalibration with each dataset and cannot easily interpolate gaps in the dataset and cannot easily extrapolate data beyond the bounds of the dataset, they have been found relatively easy to be made and the uncertainty in their results can be quantified. The least accurate type of formulation approach-based modelling is graphical models since they are simplification based on analytical, empirical, or statistical models.

As to the main input variable-based modelling type, it has been found that average speed models result in modelling errors reach 57% in comparison with field data but they are most helpful in estimating aggregate emissions inventories and are highly relevant to road traffic. It has been found as well that instantaneous speed models are more accurate in estimating vehicle emissions than average speed models in terms of both their absolute magnitude and their relative trends. In addition, it has been found that specific power models are more suitable for heavy duty diesel vehicle engines.

In the state variable value-based type of modelling, it has been found that the crank-angle resolution-based models are the most accurate models in this classification although they usually require a relatively long computational time for their complexity and thus they are less suitable for vehicle powertrain fuel consumption and emissions control applications and therefore are less relevant to road traffic than the mean value-based models. The mean value-based models strike a balance between modelling accuracy and computational efficiency and therefore are very suitable for vehicle powertrain fuel consumption and emissions control applications.

In the number of dimensions-based modelling type, it has been found that the zero/one dimensional/single zone models are the most computationally efficient models in this classification because of their simplicity and thus are most suitable for vehicle powertrain fuel consumption and emissions control applications and therefore are most relevant to road traffic. Yet, the zero/one dimensional/single zone models are the least accurate modelling subcategory in this classification. In contrary of that the multi-dimensional/multi-zone models are the most accurate modelling subcategory in this classification because they account for spatial variation in mixture composition and temperature in the cylinder charge. However, the multi-dimensional/multi-zone models require relatively long computational time and their usually included phenomenological sub-models result in having results that may vary according to the assumed initial or boundary conditions in these sub-models. The quasi dimensional models subcategory lies somewhere in-between these two extremes since the quasi dimensional models strike a balance between modelling accuracy and computational efficiency.

A major challenge in this research area is to bridge the gap between the accuracy of microscopic modelling simulations and the scalability of macroscopic modelling simulations. Scaling up microscopic modelling simulations to macroscale allows engineers to address detailed research questions at a truly large-scale helping in assessing and developing transportation applications accurately. Yet, such scaling up of microscopic modelling simulations to the aggregate level of macroscopic modelling requires supercomputers and much optimisation of the code (Demers et al., 2009). Another major challenge in this research area is that microscale models of particulate matter (PM) emission estimates have not been fully developed yet. This can be addressed by the further developments of PHEM and VERSIT models although this is dependent on the availability of a comprehensive PM emissions dataset. However, given this lack of data, it is not yet clear whether existing modelling techniques will prove adequate for PM emission estimates (North, 2006).

5 Conclusions

This review has categorised vehicle fuel consumption and emissions models into five classifications three of which were suggested by other researchers and the rest have been suggested by this research. The three classifications suggested by other researchers are the scale of the input variable-based modelling, state variable value-based modelling, and number of dimensions-based modelling. The classifications suggested by this research are the formulation approach-based modelling and main input variable-based modelling. The key relevant models to each of these categories have been presented. The analysis of vehicle fuel consumption and emission rates based on modelling indicated that vehicle fuel consumption and emission rates increase considerably as the number of vehicle stops increases especially at high cruise speed. These models have been then compared with regard to assumptions, limitations, merits, drawbacks, characteristic parameters, data collection technique, accuracy, and relevance to traffic. In these models the main input variables and parameters for modelling are vehicle's average speed, vehicle's average acceleration, vehicle's instantaneous speed, vehicle's instantaneous acceleration, and engine specific power. It has been found that the trends of vehicle fuel consumption and emissions provided by current models are generally satisfactorily close to field data trends.

As to the scale of the input variable-based modelling classification, it has been found that microscopic modelling, as much as the accuracy of the instantaneous speed-based modelling type in the main input variable-based modelling classification, is the most accurate type of modelling in this classification. In this classification, mesoscopic modelling has proved to strike a balance between simplicity and accuracy and is thus the most suitable subcategory in this classification for transportation and control applications. In addition, macroscopic modelling has been found highly relevant to road traffic and most helpful in estimating aggregate emissions inventories.

Analytical modelling has been found to be the most accurate type of modelling in the formulation approach-based modelling classification. The study has found that empirical modelling strikes a balance between simplicity and accuracy and is thus the most suitable subcategory in this classification for transportation and control applications. In addition, graphical modelling has been found to be the easiest type of modelling in this classification to be recognised and understood visually.

In the state variable value-based modelling classification, crank angle resolution-based modelling type has been found to be the most accurate type of modelling in this classification. In addition, mean value-based modelling has been found to be the most suitable type of modelling for transportation and control applications.

Multi-dimensional modelling has been found to be the most accurate type of modelling in the number of dimensions-based modelling classification. It has been found in this research that quasi dimensional modelling strikes a balance between simplicity and accuracy and is thus the most suitable subcategory in this classification for control applications. In addition, zero/one dimensional modelling has been found to be most helpful in estimating aggregate emissions inventories.

It has been found that none of the presented models is totally suitable for transportation and control applications. It has been found as well that INTEGRATION and CORSIM appear to have the highest probability of success in real world applications. In addition, with more calibration and validation AIMSUN and PARAMICS can be brought to the forefront for use in transportation applications.

Among the key future directions of research in this research area is to implement truly scalable micro-simulations for large transportation networks (Demers et al., 2009). Another key future direction is to investigate the optimal distributions of one- and two-lane sections for roads without oncoming traffic. An additional promising research direction is to characterise analytically the relationships, if any, between the driver's throttle input and the vehicle conditions, roadway conditions, and surrounding traffic conditions. A further key future direction is to develop a flexible simulation tool to simulate the use of advanced driver assistance systems (ADASs), such as virtual rumble strips, intelligent speed adaptation, and adaptive cruise control, on rural roads. The development of calibration standards for such models and for other traffic models used for air quality analysis is a promising relevant research direction.

Electrification of vehicles has emerged as an emerging research area that has been recently exhibiting much interest for increasing powertrain efficiency, reducing fuel consumption, and reducing GHG emissions. Modelling such technology is a promising research area. A key element in this area is the development of system-level modellers and simulators of different levels of hybridisation, from mild hybrid to full electric vehicles, depending on the vehicle use pattern. Extending the existing models of thermal engines and after-treatment for addressing usage of alternative fuels is a relevant promising research direction. By coupling these extended models with the various hybrid powertrain component models, transient effects related to engine start/stop, engine warm-up, battery management, and after treatment light-off can be accurately identified. This can become further interesting if these models are developed such that to be multi-scalable, i.e., to be usable during all phases of the development process from concept design, system optimisation, and sub-system optimisation up to real-time HiL applications during final system validation. At the component level, the currently available multi-dimensional simulation models need to be suitably extended to optimise the design of the future hybrid and full electric powertrain related components, such as modern battery modules, power electronics, and electric motors, and their operation. For instance, modelling the cooling subsystems of these components requires multi-physics capabilities that simultaneously account for coupled flow/heat transfer phenomena, electro-chemistry effects, and electro-magnetic effects.

In order to account for future alternative fuels and their impact on combustion efficiency and emission characteristics, the currently existing engine and after-treatment simulation models need to be extended as well. The different physical and combustion properties of the various alternative fuels need to be taken into account in the detailed models for fuel injection, auto-ignition and combustion as well as pollutant formation and their after-treatment. The system-level engine and after-treatment models need to be extended as well in order to reflect the impact of future fuels on engine performance and hence onto GHG emissions characteristics in real vehicle drive cycles. An additional future research prospect is the combination of this system-level modelling with traffic simulation tools which can allow investigating more precisely the impact of new vehicle concepts and alternative fuels on local emissions, such as PM, NOx, CO, HC as well as on noise.

The trend of developing reduced-weight, down-sized, and low-friction internal combustion engines has opened another promising research horizon for advanced simulation tools and methods development. An integrated optimisation approach is needed to model the friction heat generation in the piston-liner contact area, oil flow in the main bearing area, and component heat up in the main bearing area. The sought integrated optimiser should enable detailed component analysis along with serving as the basis for parameterisation of system-level thermal analysis models (Tapani, 2005).

An additional promising research direction is modelling the interactive dynamic behaviour of the crankshaft/connecting-rod/piston-assembly in reciprocating internal combustion engines and investigating its influence on fuel efficiency through frictional losses. This can be driven by modelling the piston secondary motions (piston-slap and piston-tilting), structural deformations of the piston rings, the dynamic behaviour of the piston ring within the piston groove, the hydrodynamic frictional losses of the piston skirt, and the elasto-hydrodynamic frictional losses of the piston rings (Tapani, 2005).

References

Aceves, S.M., Flowers, D.L., Martinez-Frias, J., Smith, J.R., Dibble, R., Au, M. and Girard, J. (2001) 'HCCI combustion: analysis and experiments', SAE International, paper # 2001-01-2077.

Aceves, S.M., Flowers, D.L., Westbrook, C.K., Smith, J.R., Pitz, W., Dibble, R., Christensen, M. and Johansson, B. (2000) 'A multi-zone model for prediction of HCCI combustion and emissions', *SAE 2000 World Congress*, Detroit, MI, USA, paper # 2000-01-0327.

Ahn, K. (1998) 'Microscopic fuel consumption and emission modelling', Master of Science Thesis, Virginia Polytechnic Institute and State University.

Ahn, K. (2002) 'Modelling light duty vehicle emissions based on instantaneous speed and acceleration levels', PhD dissertation, Virginia Polytechnic Institute and State University.

Ahn, K. and Trani, A. (1999) 'Microscopic fuel consumption and emission modelling', *Proceedings of the 78th Annual Meeting of the Transportation Research Board*, Washington, DC.

Ahn, K., Rakha, H., Trani, A. and Van Aerde, M. (2002) 'Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels', *Journal of Transportation Engineering*, Vol. 128, No. 2, pp.182–190.

Ajtay, D. and Weilenmann, M. (2004) 'Static and dynamic instantaneous emission modelling', *International Journal of Environment and Pollution*, Vol. 22, No. 3, pp.226–239.

Akcelik, R. (1985) 'An interpretation of the parameters in the simple average travel speed model of fuel consumption', *Australian Road Research*, Vol. 15, pp.46–49.

Al-qaimari, G., Kilgour, A.C. and Paton, N.W. (1995) 'Visualising data modelling constructs in an object-oriented database', *Proceedings of the 7th International Conference on Information Systems Engineering (CAiSE'95) – Workshop on End User Development*.

Amsden, A.A., Ramshaw, J.D., O'Rourke, P.J. and Dukowicz, J.K. (1985) *KIVA: A Computer Program for Two- and Three-Dimensional Fluid Flow with Chemical Reactions and Fuel Sprays*, Los Alamos National Laboratory Report LA-10245-MS, USA.

An, F., Barth, M., Norbeck, J. and Ross, M. (1997) 'Development of comprehensive modal emissions model: operating under hot-stabilized conditions', *Transportation Research Record, J. of the Transportation Research Board, National Academy of Sciences*, Record No. 1587, pp.52–62.

Anderson, L.R. (1979) *Decoupling and Reduced Order Modelling of Two Time Scale Systems*, Arizona University Publications, Arizona, USA.

Anderson, W.P., Kanaroglou, P.S., Miller, E.J. and Buliung, R.N. (1996) 'Simulating automobile emissions in an integrated urban model', *Transportation Research Record: Journal of the Transportation Research Board*, Record No. 1520, pp.71–80.

Andersson, P. and Eriksson, L. (2004) 'Cylinder air charge estimator in turbocharged SI-engines', SAE International, paper # 2004-01-1366.

Ang, B.W. (1990) 'The effects of maintenance on the fuel efficiency of public buses', *Energy*, Vol. 15, No. 12, pp.1099–1105.

Archilla, A.R. and De Cieza, A.O.F. (1999) 'Truck performance on Argentinean highways', *Transportation Research Record*, Record No. 1555, pp.114–123.

Arregle, J., López, J.J., García, J.M. and Fenollosa, C. (2003) 'Development of a zero-dimensional diesel combustion model: part 2: analysis of the transient initial and final diffusion combustion phases', *Applied Thermal Engineering*, Vol. 23, No. 11, pp.1319–1331.

Arsie, I., Di Genova, F., Mogavero, A., Pianese, C., Rizzo, G., Caraceni, A., Cioffi, P. and Flauti, G. (2006) 'Multi-zone predictive modelling of common-rail multi-injection diesel engines', SAE International, paper # 2006-01-1384.

Arsie, I., Di Genova, F., Pianese, C., Rizzo, G., Caraceni, A., Cioffi, P. and Flauti, G. (2005) 'Thermodynamic modelling of jet formation and combustion in common rail multi-jet diesel engines', SAE International, paper # 2005-01-1121.

Arsie, I., Pianese, C. and Sorrentino, M. (2007) 'Control parameters optimization in automotive diesel engines via two zone modelling', *Proceedings of the Fifth IFAC Symposium on Advances in Automotive Control (2007), Advances in Automotive Control*, Vol. 5, No. 1.

Assanis, D., Delagrammatikas, G., Fellini, R., Filipi, Z., Liedtke, J., Michelena, N., Papalambros, P., Reyes, D., Rosenbaum, D., Sales, A. and Sasena, M. (1999) 'An optimization approach to hybrid electric propulsion system design', *Mechanics of Structures and Machines*, Vol. 27, No. 4, pp.393–421.

Assanis, D.N. and Heywood, J.B. (1986) 'Development and use of a computer simulation of the turbocompounded diesel system for engine performance and component heat transfer studies', SAE International, paper # 860329.

Assanis, D.N., Filipi, Z.S., Gravante, S., Grohnke, D., Gui, X., Louca, L.S., Rideout, G.D., Stein, J.L. and Wang, Y. (2000) 'Validation and use of Simulink integrated, high fidelity, engine-invehicle simulation of the international class VI truck', *Proceedings of the SAE World Congress, 2000*, SAE International, paper # 2000-01-0288.

Austen, A.E.W. and Lyn, W.T. (1961) 'Some steps toward calculating diesel engine behavior', SAE International, paper # 409A.

Autili, M. and Pelliccione, P. (2008) 'Towards a graphical tool for refining user to system requirements', *Electronic Notes in Theoretical Computer Science*, Vol. 211, pp.147–157.

Bachman, W. and Sarasua, W. (1996) 'Geographic information framework for modelling mobile-source emissions', *Transportation Research Record*, Record No. 1551, pp.123–133.

Bachman, W. and Sarasua, W. (2000) 'Modelling regional mobile source emissions in a geographic information system framework', *Transportation Research Part C: Emerging Technologies*, Vol. 8, pp.205–229.

Ball, J.K., Bowe, M.J., Stone, C.R. and McFadden, P.D. (2000) 'Torque estimation and misfire detection using block angular acceleration', SAE International, paper # 2000-01-0560.

Bancha, T. and Jau-Huai, L. (2009) 'Single zone model for HCCI engine fueled with n-Heptane', *World Academy of Science, Engineering and Technology*, Vol. 53, pp.304–310.

Barba, C., Burkhardt, C., Boulouchos, K. and Bargende, M. (2000) 'A phenomenological combustion model for heat release rate prediction in high-speed DI diesel engines with common rail injection', SAE International, paper # 2000-01-2933.

Barth, M., An, F., Norbeck, J. and Ross, M. (1996) 'Model emission modelling: a physical approach', *Transportation Research Record*, Record No. 1520, pp.81–88.

Barth, M., Norbeck, J. and Ross, M. (1998) 'National cooperative highway research program project 25-11: development of a comprehensive modal emissions model', *Proceedings of the 77th Annual Meeting of the Transportation Research Board*, Washington, DC.

Bazari, Z. (1994) 'Diesel exhaust emissions prediction under transient operating conditions', SAE International, paper # 940666.

Bengtsson, J., Gafvert, M. and Strandh, P. (2004) 'Modelling of HCCI engine combustion for control analysis', *Proceedings of the 43rd IEEE Conference on Decision and Control*, December, Paradise Island, Bahamas, paper # WeA09.2, pp. 1682-1687.

Bi, X., Yang, M., Han, S. and Ma, Z. (1999) 'A multi-zone model for diesel spray combustion', *Proceedings of the SAE International Congress & Exposition*, March, Detroit, MI, USA, paper # 1999-01-0916.

Biggs, D.C. and Akcelik, R. (1987) 'Estimating effect of vehicle characteristics on fuel consumption', *Journal of Transportation Engineering*, Vol. 113, No. 1, pp.101–106.

Biteus, J. (2002) 'Mean value engine model of a heavy duty diesel engine', Research Report, Linköpings Universitet, Sweden.

Blizard, N.C. and Keck, J.C. (1974) 'Experimental and theoretical investigation of turbulent burning model for internal combustion engines', *SAE Transactions*, SAE Paper #740191, Vol. 86, pp.846–864.

Bohn, C., Böhme, T., Staate, A. and Manemann, P. (2006) 'A nonlinear model for design and simulation of automotive idle speed control strategies', *Proceedings of the IEEE 2006 American Control Conference*, USA.

Boulter, P.G., McCrae, I.S. and Barlow, T.J. (2007) 'A review of instantaneous emission models for road vehicles', Research Project Report # 267, Transport Research Laboratory.

Boxill, S.A. and Yu, L. (2000) 'An evaluation of traffic simulation models for supporting its development', Technical Report # SWUTC/00/167602-1, Center for Transportation Training and Research, Texas Southern University.

Bracco, F.V. (1985) 'Modelling of engine sprays', SAE International, paper # 850394.

Brace, C.J., Deacon, M., Vaughan, N.D., Charlton, S.J. and Burrows, C.R. (1994) 'Prediction of emissions from a turbocharged passenger car diesel engine using a neural network', *Proceedings of the IMechE*, paper # C484/046.

Brahma, A., Guezennec, Y. and Rizzoni, G. (2000) 'Dynamic optimization of mechanical/electrical power flow in parallel hybrid electric vehicles', *Proceedings of the 5th International Symposium on Advanced Vehicle Control (AVEC)*, Ann Arbor, MI, USA.

Brandstatter, W. (1985) 'The effect of inlet port geometry on in-cylinder flow structure', SAE International, paper # 850499.

Brehod, D.D. and Newman, C.E. (1992) 'Monte Carlo simulation of cycle by cycle variability', SAE International, paper # 922165.

Butler, K.L., Ehsani, M. and Kamath, P. (1999) 'A Matlab-based modelling and simulation package for electric and hybrid electric vehicle design', *IEEE Transactions on Vehicular Technology*, Vol. 48, No. 6, pp.1770–1778.

Butschek, M. (2000) Modelling and diagnosis of leakages in the air intake path of an automotive diesel engine', Master's thesis, Fachhochschule Trier.

Cacciari, A. and Piancastelli, L. (2001) 'Fuel consumption optimisation and power requirement reduction via multiple speed gearbox and automatic selection system for an automotive application', pp.G144–G152, XII Associazione Nazionale Disengo di Macchine (ADM) International Conference, Rimini, Italy.

California Air Resources Board (CARB) (1991) 'Methodology to calculate emission factors for on-road vehicle', California Air Resource Board, Sacramento, CA.

Canova, M., Chiara, F., Rizzoni, G. and Wang, Y. (2010) 'Model-based characterization and analysis of diesel engines with two-stage turbochargers', SAE 2010 World Congress & Exhibition, April, Detroit, MI, USA, SAE International, paper # 2010-01-1220.

Canova, M., Midlam-Mohler, S., Guezennec, Y. and Rizzoni, G. (2009) 'Mean value modelling and analysis of HCCI diesel engines with external mixture formation', *Journal of Dynamic Systems, Measurements, Control*, Vol. 131, No. 11, pp.12–26.

Cappiello, A., Chabini, I., Lue, A., Zeid, M. and Nam, E.K. (2002) *A Statistical Model of Vehicle Emissions and Fuel Consumption*, Ford-MIT Alliance Collection.

Ceccarelli, R., Canudas-de-Wit, C., Moulin, P. and Sciarretta, A. (2009) 'Model-based adaptive observers for intake leakage detection in diesel engines', *Proceedings of the IEEE American Control Conference, IEEE ACC'09*, Missouri, USA.

Chamberlin, R., Talbot, E. and Swanson, B. (2011) 'Utilizing MOVES' for estimating traffic operational emissions impacts', *Proceedings of the Transportation Planning, Land Use, and Air Quality Conference*, Texas, USA.

Chang, D.J. and Morlok, E.K. (2005) 'Vehicle speed profiles to minimize work and fuel consumption', *Journal of Transportation Engineering*, Vol. 131, No. 3, pp.173–182.

Chang, M. and Evans, L. (1981) 'Trip time versus stop time and fuel consumption characteristics in cities', *Transportation Science*, Vol. 15, No. 3, pp.183–209.

Chen, A., Veshagh, A. and Wallace, S. (1998) 'Intake flow predictions of a transparent DI diesel engine', SAE International, paper # 981020.

Cheng, W.K. and Diringer, J.A. (1991) 'Numerical modelling of SI engine combustion with a flame sheet model', *SAE Transactions*, SAE International, Paper # 910268, Vol. 100, No. 3, pp.414–421.

Cho, D. and Hedrick, J.K. (1989) 'Automotive powertrain modelling for control', *Proceedings of the ASME Journal of Dynamic Systems, Measurement, and Control*.

Cho, H., Song, H., Lee, J. and Kauh, S. (2001) 'Simulation of a transient torque response for engine performance in a spark ignition engine', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*.

Cook, J.A. and Powell, B.K. (1987) 'Modelling of an internal combustion engine for control analysis', *Proceedings of the American Control Conference*, Minneapolis, Minnesota, USA.

Cook, J.A., Sun, J., Buckland, J.H., Kolmanovsky, I.V., Peng, H. and Grizzle, J.W. (2006) 'Automotive powertrain control – a survey', *Asian Journal of Control*, Vol. 8, No. 3, pp.237–260.

Davis, N., Lents, J., Osses, M., Nikkila, N. and Barth, M.J. (2005) 'Development and application of an international vehicle emissions model: attachment C: characterizing emission variations due to driving behavior from on-road vehicles', *Transportation Research Record: Journal of the Transportation Research Board*, Record No. 1939.

Daw, C.S., Edwards, K.D., Finney, C.E.A. and Wagner, R.M. (2009) 'A simple model for exploring the cyclic dynamics of spark-assisted HCCI', *Proceedings of the 6th US National Combustion Meeting*.

Daw, C.S., Green, J.B., Thomas, J.F., Kennel, M.B., Finney, C.E.A. and Connolly, F.T. (1996) 'A simple model for cyclic variations in a spark-ignition engine', *Proceedings of the 1996 Technical Meeting of the Central States Section of the Combustion Institute*.

Daw, C.S., Kennel, M.B., Finney, C.E.A. and Connolly, F.T. (1998) 'Observing and modelling nonlinear dynamics in an internal combustion engine', *Physical Review E*, Vol. 57, No. 3.

De Nicolao, G., Scattolini, R. and Siviero, C. (1996) 'Modelling the volumetric efficiency of IC engines: parametric, non-parametric and neural techniques', *Control Engineering Practice*, Vol. 4, No. 10, pp.1405–1415.

Delagrammatikas, G. and Assanis, D.N. (2001) 'The reverse engineering of a turbocharged diesel engine through a unified systems approach', SAE International, paper # 01-1244, 2001.

Delosh, R.G., Brewer, K.J., Buch, L.H., Ferguson, T.F.W. and Tobler, W.E. (1981) 'Dynamic computer simulation of a vehicle with electronic engine control', SAE International, paper 810447.

Demers, A., Gao, O., Gehrke, J., Koch, C., Vaz Salles, M. and White, W. (2009) 'Scaling transportation simulations through declarative processing', *Proceedings of the Next Generation Data Mining Summit NGDM '09*, Columbia, USA.

Ding, Y. (2000) 'Quantifying the impact of traffic-related and driver-related factors on vehicle fuel consumption and emissions', Master thesis, Virginia Polytechnic Institute and State University.

Ding, Y. and Rakha, H. (2004) 'Trip-based explanatory variables for estimating vehicle fuel consumption and emission rates', *Journal of Water, Air, & Soil Pollution: Focus*, Vol. 2, Nos. 5–6, pp.61–77.

Dohner, D.J. (1980) 'A mathematical engine model for development of dynamic engine control', SAE International, paper # 800054.

Dovifaaz, X., Oulandsine, M., Rachid, A. and Bloch, G. (2002) 'Neural modelling for diesel engine control', *Proceedings of the 15th Triennial World Congress*, Barcelona, Spain.

dSPACE GmbH (2006) *Dynamic Models for Deutz Diesel Power*, dSPACE GmbH, Germany.

Durgun, O. and Sahin, Z. (2009) 'Theoretical investigation of heat balance in direct injection (DI) diesel engines for neat diesel fuel and gasoline fumigation', *Energy Conversion and Management*, Vol. 50, No. 1, pp.43–51.

Durrani, S., Zhou, X. and Chandra, A. (2010) 'Effect of vehicle mobility on connectivity of vehicular ad hoc networks', *Proceedings of the IEEE Vehicular Technology Conference (VTC2010-Fall)*, Canada.

Easley, W.L., Agarwal, A. and Lavoie, G.A. (2001) 'Modelling of HCCI combustion and emissions using detailed chemistry', *SAE 2001 World Congress*, Detroit, MI, USA, paper # 2001-01-1029.

Elmqvist, H., Mattsson, S.E., Olsson, H., Andreasson, J., Otter, M., Schweiger, C. and Brück, D. (2004) 'Realtime simulation of detailed vehicle and powertrain dynamics', SAE International, paper # 04AE-31.

Eriksson, L. (2007) 'Modelling and control of turbocharged SI and DI engines', *Oil &Gas Science and Technology – Rev. IFP*, Vol. 62, No. 4, pp.523–538.

Eriksson, L., Nielsen, L., Brugard, J., Bergstrom, J., Pettersson, F. and Andersson, P. (2002) 'Modelling and simulation of a turbo charged SI engine', *Annual Reviews in Control*, Vol. 26, No. 1, pp.129–137.

Eriksson, L., Wahlström, J. and Klein, M. (2010) 'Automotive model predictive control', *Lecture Notes in Control and Information Sciences*, Vol. 402, pp.53–71.

Esteves-Booth, A., Muneer, T., Kubie, J. and Kirby, H. (2002) 'A review of vehicular emission models and driving cycles', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 216, No. 8.

Evans L. and Herman, R. (1978) 'Automobile fuel economy on fixed urban driving schedules', *Transportation Science*, Vol. 12, No. 2, pp.137–152.

Evans, L. and Herman, L. (1976) 'Multivariate analysis of traffic factors related to fuel consumption in urban driving', *Transportation Science*, Vol. 10, No. 2, pp.205–215.

Ewalds, R. (2003) 'TNO DYNAMO – user guide', TNO Automotive Internal Report.

Fang, F.C. and Elefteriadou, L. (2008) 'Capability-enhanced microscopic simulation with real-time traffic signal control', *IEEE Transactions on Intelligent Transportation Systems*, Vol. 9, No. 4, pp.625–632.

Feng, C. (2007) 'Transit bus load-based modal emission rate model development', PhD dissertation, Georgia Institute of Technology.

Filipi, Z.S. and Assanis, D.N. (2001) 'A nonlinear, transient, single-cylinder diesel engine simulation for predictions of instantaneous engine speed and torque', *Journal of Engineering Gas Turbines Power*, Vol. 123, No. 4, pp.951–959.

Flower, J.O. and Gupta, R.K. (1974) 'Optimal control considerations of diesel engine discrete models', *International Journal of Control*, Vol. 19, No. 6, pp.1057–1068.

Foster, D.E. (1985) 'An overview of zero-dimensional thermodynamic models for I.C. engine data analysis', SAE International, paper # 852070.

Frey, H.C., Rouphail, N.M., Zhai, H., Farias, T.L. and Gonçalves, G.A. (2007) 'Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions', *Transportation Research Part D: Transport and Environment*, Vol. 12, No. 4, pp.281–291.

Froschhammer, F., Mathiak, D. and Rabenstein, F. (2006) 'Hochdynamische prüfstände – ein werkzeug für die insta-tionärapplikation', *ATZ/MTZ Konferenz – Motor*, Motorenentwick-lung auf dynamischen Prüfständen, Wiesbaden.

Froschhammer, F., Schittenhelm, M. and Keppler, R. (2009) *BMW High-Dynamic Engine Test Benches using SIMPACK Real-Time Models*, SIMPACK Publications, SIMPACK, Gilching, Germany.

Gao, D.W., Mi, C. and Emadi, A. (2007) 'Modelling and simulation of electric and hybrid vehicles', *Proceedings of IEEE*.

Gatowski, J.A., Balles, E.N., Chun, K.M., Nelson, F.E., Ekchian, J.A. and Heywood, J.B. (1984) 'Heat release analysis of engine pressure data', SAE International, paper # 841359.

Genta, G. (2003) *Motor Vehicle Dynamics: Modelling and Simulation*, World Scientific, Singapore.

Gerdes, J.C. and Hedriek, J.K. (1997) 'Vehicle speed and spacing control via coordinated throttle and brake actuation', *Control Engineering Practice*, Vol. 5, No. 11, pp.1607–1614.

Gissinger, G.L., Renard, R. and Hassenforder, M. (1989) 'Model based design and control of diesel engines', SAE International, paper # 890568.

Gning, A.C., Mihaylova, L. and Boel, R. (2011) 'Interval macroscopic models for traffic networks', *IEEE Transactions on Intelligent Transportation Systems*, Vol. 12, No. 2, pp.523–536.

Gouldin, F.C. (1987) 'An application of fractals to modelling premixed turbulent flames', *Combustion & Flame*, Vol. 68, No. 3, pp.249–266.

Grossi, F., Palladino, A., Zanasi, R. and Fiengo, G. (2009) 'The power-oriented graphs technique for modelling engine dynamics based on electrical analogy', *Proceedings of the American Control Conference*.

Guensler, R.L., Washington, S.P., Sperling, D. (1993) 'A weighted disaggregate approach to modelling speed correction factors', Institute of Transportation Studies, University of California, Davis, Research Report # UCD-ITS-RR-93-06.

Guzzella, L. and Amstutz, A. (1998) 'Control of diesel engines', *IEEE Control Systems*, Vol. 18, No. 5, pp.53–71.

Hallmark, S.L., Fomunung, I., Guensler, R. and Bachman, W. (2000) 'Assessing impacts of improved signal timing as a transportation control measure using an activity-specific modelling approach', *Proceedings of the Annual Meeting of the Transportation Research Board*.

Harris, H.D. and Pearce, F. (1990) 'A universal mathematical model of diesel engine performance', *Journal of Agriculture Engineering Research*, Vol. 47, No. 4, pp.165–176.

Havstad, M.A., Aceves, S.M., McNenly, M.J., Piggott, W.T., Edwards, K.D., Wagner, R.M., Daw, C.S. and Finney, C.E.A. (2010) 'Detailed chemical kinetic modelling of Iso-octane SI-HCCI', *SAE 2010 World Congress*, Detroit, MI, USA, paper # 10PEL-0840.

Hellström, E. (2010) 'Look-ahead control of heavy vehicles', PhD dissertation, Linköpings Universitet, Sweden.

Hendricks, E. (1986) 'A compact, comprehensive model of large turbocharged, two-stroke diesel engines', SAE International, paper # 861190.

Hendricks, E. (1989) 'Mean value modelling of large turbocharged two-stroke diesel engines', SAE International, paper # 890564.

Hendricks, E. (1997) 'Engine modelling for control applications: a critical survey', *Meccanica Journal*, Vol. 32, No. 5, pp.387–396.

Hendricks, E. (2001) 'Isothermal vs. adiabatic mean value SI engine models', *Proceedings of the 3rd IFAC Workshop, Advances in Automotive Control*, Preprints, Karlsruhe, Germany, pp.373–378.

Hendricks, E. and Sorenson, S.C. (1990) 'Mean value modelling of spark ignition engines', SAE International, paper # 900616.

Herweg, R. and Maly, R.R. (1992) 'A fundamental model for flame kernel formation in S.I. engines', *SAE Transactions*, SAE International, paper # 922243, Vol. 101, pp.1947–1976.

Heywood, J. (1988) *Internal Combustion Engine Fundamentals*, McGraw Hill, New York, NY.

Heywood, J.B. (1994) 'Combustion and its modelling in spark-ignition engines', *Proceedings of the International Symposium COMODIA 94*, paper # C94_P001.

Hillion, M., Chauvin, J. and Petit, N. (2009) 'Combustion control of an HCCI diesel engine with cool flame phenomenon', *Proceedings of the European Control Conference 2009*, Budapest, Hungary, paper # WeA10.5, pp.3827–3832.

Hillion, M., Chauvin, J., Grondin, O. and Petit, N. (2008) 'Active combustion control of diesel HCCI engine: combustion timing', SAE International, paper # 2008-01-0984.

Hrovat, D. and Sun, J. (1997) 'Models and control methodologies for IC engine idle speed control design', *Journal of Control Engineering Practice*, Vol. 5, No. 8, pp.1093–1100.

Hung, W., Tong, H. and Cheung, C. (2005) 'A modal approach to vehicular emissions and fuel consumption model development', *Journal of the Air and Waste Management Association*, Vol. 55, No. 10, pp.1431–1440.

INRO Consultants (1996) *EMME/2 User's Manual, Release 8*, INRO Consultants, Montreal, CA.

Jankovic, M., Jankovic, M. and Kolmanovsky, I. (2000) 'Constructive Lyapunov control design for turbocharged diesel engines', *IEEE Transactions on Control Systems Technology*, Vol. 8, No. 2, pp.288–299.

Jennings, M.J., Blumberg, P.N. and Amann, R.W. (1986a) 'A dynamic simulation of the Detroit diesel electronic control system for evaluating engine and driveline interactions', *Proceedings of the Dynamic Simulation – American Control Conference*, paper # WA9-9:30, pp.243–251.

Jennings, M.J., Blumberg, P.N. and Amann, R.W. (1986b) 'A dynamic simulation of the Detroit diesel electronic control system in heavy duty truck powertrains', SAE International, paper # 861959.

Jensen, J.P., Kristensen, A.F., Sorenson, S.C., Houbak, N. and Hendricks, E. (1991) 'Mean value modelling of a small turbocharged diesel engine', SAE International, paper # 910070.

Joumard, R., Philippe, F. and Vidon, R. (1999) 'Reliability of the current models of instantaneous pollutant emissions', *The Science of the Total Environment*, Vol. 235, Nos. 1–3, pp.133–142.

Jung, D. and Assanis, D.N. (2001) 'Multi-zone DI diesel spray combustion model for cycle simulation studies of engine performance and emissions', SAE International, paper # 2001-01-1246.

Kabir, M.N., Issa-Salwe, A. and Ahmed, M. (2010) 'Simplified model of combustion process in a diesel engine for real-time operation', *International Journal of Vehicle Systems Modelling and Testing*, Vol. 5, No. 4, pp.347–357.

Kao, M. and Moskwa, J.J. (1995) 'Turbocharged diesel engine modelling for nonlinear engine control and state estimation', *ASME Transactions, Journal of Dynamic Systems, Measurement and Control*, Vol. 117, No. 1, pp.20–30.

Karlsson, F. (2001) 'Modelling the intake manifold dynamics in a diesel engine', Master's thesis, Linkopings Universitet.

Karlsson, J. and Fredriksson, J. (1999) 'Cylinder-by-cylinder engine models vs. mean value engine models for use in powertrain control applications', *SAE International Congress and Exhibition 1999*, Detroit, MI, USA, paper # 1999-01-0906.

Karmiggelt, R. (1998) 'Mean value modelling of a spark ignition engine', Research Report, Eindhoven University of Technology.

Kent, J.H. and Mudford, N.R. (1979) 'Motor vehicle emissions and fuel consumption modelling', *Transportation Research Part A: General*, Vol. 13, No. 6, pp.395–406.

Khayyam, H., Kouzani, A., Khoshmanesh, K. and Hu, E. (2008) 'Power analysis and simulation of a vehicle under combined loads', *Proceedings of the 4th International Green Energy Conference (IGEC-IV 2008)*, North China Electric Power University (NCEPU), Beijing, China, pp.855–871.

Killingsworth, N., Aceves, S., Flowers, D. and Krstic, M. (2006) 'A simple HCCI engine model for control', *Proceedings of the IEEE International Conference on Control Applications*, Munich, Germany.

Kim, H.M., Kokkolaras, M., Louca, L.S., Delagrammatikas, G.J., Michelena, N.F., Filipi, Z.S., Papalambros, P.Y., Stein, J.L. and Assanis, D.N. (2002) 'Target cascading in vehicle redesign: a class VI truck study', *International Journal of Vehicle Design*, Vol. 29, No. 3, pp.199–225.

Kim, K. and Kim, D. (1999) Improving the NOx-BSFC trade off of a turbocharged large diesel engine using performance simulation', Research Report, Hyundai Heavy Industries Co., Ltd.

Klein, M. and Eriksson, L. (2002) 'Models, methods and performance when estimating the compression ratio based on the cylinder pressure', *Proceedings of the CCSSE*, Linkopings Universitet, Sweden.

Klein, M., Eriksson, L. and Aslund, J. (2004) 'Compression ratio estimation based on cylinder pressure data', *Proceedings of the IFACWS'04*.

Kolmanovsky, I., Moraal, P., van Nieuwstadt, M. and Stefanopoulou, A. (1997) 'Issues in modelling and control of intake flow in variable geometry turbocharged engines', *Proceedings of the 18th IFIP Conference on System Modelling and Optimization*, Detroit, USA.

Komninos, N.P. and Hountalas, D.T. (2008) 'Improvement and validation of a multi-zone model for HCCI engine combustion concerning performance and emissions', *Energy Conversion and Management*, Vol. 49, No. 10, pp.2530–2537.

Komninos, N.P., Hountalas, D.T. and Kouremenos, D.A. (2005) 'Description of in-cylinder combustion processes in HCCI engines using a multi-zone model', *SAE 2005 World Congress & Exhibition*, Detroit, MI, USA, paper # 2005-01-0171.

Kulkarni, M.M. Sinha, R.P. and Dhariwal, H.C. (1992) 'Reduced order model of turbo charged diesel engine', *Proceedings of the American Control Conference, Green Valley*, Vol. 2, pp.927–931.

Lansky, L. (2008) 'Diesel engine modelling and control', Master's thesis, Czech Technical University in Prague.

Lavoie, G.A. and Blumberg, P.N. (1980) 'A fundamental model for predicting fuel consumption, NOx and HC emissions of the conventional spark-ignited engine', *Journal of Combustion Science and Technology*, Vol. 21, No. 5, pp.225–258.

Lei, W., Chen, H. and Lu, L. (2010) 'Microscopic emission and fuel consumption modeling for light-duty vehicles using portable emission measurement system data', *World Academy of Science, Engineering and Technology*, Vol. 66, pp.918–925.

Leung, D.Y.C. and Williams, D.J. (2000) 'Modelling of motor vehicle fuel consumption and emissions using a power-based model', *Environmental Monitoring and Assessment*, Vol. 65, Nos. 1–2, pp.21–29.

Li, K. and Ioannou, P. (2004) 'Modelling of traffic flow of automated vehicles', *IEEE Transactions on Intelligent Transportation Systems*, Vol. 5, No. 2, pp.99–113.

Liao, T. and Machemehl, R.B. (1998) 'Development of an aggregate fuel consumption model for signalized intersections', *Transportation Research Record*, No. 1641, pp.9–18.

Lindhjem, C.E., Pollack, A.K., Slott, R.S. and Sawyer, R.F. (2004) 'Analysis of EPA's draft plan for emissions modelling in MOVES and MOVES GHG', Research Report # CRC Project E-68, ENVIRON International Corporation.

Liu, Z. and Chen, R. (2009) 'A zero-dimensional combustion model with reduced kinetics for SI engine knock simulation', *Combustion Science and Technology*, Vol. 181, No. 6, pp.828–852.

Livengood, J.C. and Wu, P.C. (1955) 'Correlation of auto ignition phenomena in internal combustion engines and rapid compression machine', *Proceedings of the 5th International Symposium on Combustion*, pp.347–356.

Lloyd, V. and Rudd, C. (2007) 'Service design', The Stationary Office (TSO), p.92.

Louca, L.S., Stein, J.L. and Rideout, D.G. (2001) 'Integrated proper vehicle modelling and simulation using a bond graph formulation', *Proceedings of the International Conference on Bond Graph Modelling*, Phoenix, AZ, Published by the Society for Computer Simulation, San Diego, CA, ISBN 1-56555-221-0.

Marsden, G., Bell, M. and Reynolds, S. (2001) 'Towards a real-time microscopic emissions model', *Transportation Research Part D*, Vol. 6, No. 1, pp.37–60.

McMahon, D.H., Hedrick, J.K. and Shladover, S.E. (1990) 'Vehicle modelling and control for automated highway systems', *Proceedings of the American Control Conference (ACC) of 1990*, Vol. 1, pp.297–303.

Metallidis, P. and Natsiavas, S. (2003) 'Linear and nonlinear dynamics of reciprocating engines', *International Journal of Non-Linear Mechanics*, Vol. 38, No. 5, pp.723–738.

Metghalchi, M. and Keck, J.C. (1980) 'Laminar burning velocity of propane-air mixtures at high temperature and pressure', *Combustion Flame*, Vol. 38, pp.143–154.

Mianzo, L. (2000) 'A transmission model for hardware-in-the-loop powertrain control system software development', *Proceedings of the 2000 IEEE International Conference on Control Applications Anchorage*, Alaska, USA, paper # MA2-5.

Millington, B.W. and Hartles, E.R. (1968) 'Frictional losses in diesel engines', *SAE Transactions*, SAE International, paper # 68-0590, Vol. 77, pp.1–10.

Moskwa, J.J. (1988) 'Automotive engine modelling for real time control', PhD thesis, Massachusetts Institute of Technology.

Moskwa, J.J. and Hedrick, J.K. (1992) 'Modelling and validation of automotive engines for control algorithm development', *Journal of Dynamic Systems, Measurements, Control*, Vol. 114, No. 2, pp.278–286.

Moulin, P. and Chauvin, J. (2009) 'Modelling and control of the air system of a turbocharged gasoline engine', *Control Engineering Practice*, Vol. 19, No. 3, pp.287–297.

Mukherjee, A. and Karmakar, R. (2000) *Modelling and Simulation of Engineering Systems through Bondgraphs*, Narosa, New Delhi, India.

National Research Council (NRC) (1995) *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*, Transportation Research Board National Research Council, Washington, DC.

Newman, P.W.G., Alimoradian, B. and Lyons, T.J. (1989) 'Estimating fleet fuel consumption for vans and small trucks', *Transportation Science*, Vol. 23, No. 1, pp.46–50.

Ni, D. and Henclewood, D. (2008) 'Simple engine models for vehicle infrastructure integration-enabled in-vehicle applications', *IEEE Transactions on Vehicular Technology*, Vol. 57, No. 5, pp.2695–2702.

Nieuwoudt, A., McCorquodale, M.S., Borno, R.T. and Massoud, Y. (2006) 'Accurate analytical spiral inductor modelling techniques for efficient design space exploration', *IEEE Electron Device Letters*, Vol. 27, No. 12, pp.998–1001.

Nilsson, Y., Eriksson, L. and Gunnarsson, M. (2008) 'Torque modelling for optimising fuel economy in variable compression engines', *International Journal of Modelling, Identification and Control (IJMIC)*, Vol. 3, No. 3, pp.327–339.

Noland, R.B. and Quddus, M.A. (2006) 'Flow improvements and vehicle emissions: effects of trip generation and emission control technology', *Transportation Research Part D*, Vol. 11, No. 1, pp.1–14.

North, R.J. (2006) 'Assessment of real-world pollutant emissions from a light-duty diesel vehicle', Doctor of Philosophy Dissertation, Imperial College London.

Nyberg, M. and Sutte, T. (2004) 'Model based diagnosis of the air path of an automotive diesel engine', *Control Engineering Practice*, Vol. 12, No. 5, pp.513–525.

Oberg, S. (2001) 'Identification and improvements of an automotive diesel engine model purposed for model based diagnosis', Research Report for DaimlerChrysler AG, MSc thesis, Linkopings Universitet.

Organisation for Economic Co-operation and Development (2002) 'Strategies to reduce greenhouse gas emissions from road transport: analytical methods', Research Report ITRD No. E109210, Organisation for Economic Co-operation and Development.

Ottikkutti, P., Van Gerpen, J. and Cui, K.R. (1991) 'Multizone modelling of a fumigated diesel engine', SAE International, paper # 910076.

Ouladsine, M., Bloch, G. and Dovifaaz, X. (2004) 'Neural modelling and control of a diesel engine with pollution constraints', Research Report, Domaine Universitaire de Saint-Jérôme.

Panis, L.I., Broekx, S. and Liu, R. (2006) 'Modelling instantaneous traffic emission and the influence of traffic speed limits', *Science of the Total Environment*, Vol. 371, Nos. 1–3, pp.270–285.

Panis, L.I., De Vlieger, I., Pelkmans, L. and Schrooten, L. (2007) 'Effect of speed reduction on emissions of heavy duty lorries', *Proceedings of the 8th Highway and Urban Environment Symposium*, pp.53–61, Springer.

Park, J.Y., Noland, R.B. and Polak, J.W. (2001) 'A microscopic model of air pollutant concentrations: comparison of simulated results with measured and macroscopic estimates', *Transportation Research Record*, Vol. 1750, pp.64–73.

Patterson, M.A., Kong, S.C., Hampson, G.J. and Reitz, R.D. (1994) 'Modelling the effects of fuel injection characteristics on diesel engine soot and NOx emissions', SAE International, paper # 940523.

Paul, B. and Ganesan, V. (2010) 'Flow field development in a direct injection diesel engine with different manifolds', *International Journal of Engineering, Science and Technology*, Vol. 2, No. 1, pp.80–91.

Pisu, P. and Rizzoni, G. (2007) 'A comparative study of supervisory control strategies for hybrid electric vehicles', *IEEE Transactions on Control Systems Technology*, Vol. 15, No. 3, pp.506–518.

Pitchford, M. and Johnson, B. (1993) 'Empirical model of vehicle emissions', *Journal of Environmental Science and Technology*, Vol. 27, No. 4, pp.741–748.

Powell, B.K. (1979) 'A dynamic model for automotive engine control analysis', *Proceedings of the 18th IEEE Conf Decision and Control*, pp.120–126.

Powell, B.K., Bailey, K.E. and Cikanek, S.R. (1998) 'Dynamic modelling and control of hybrid electric vehicle powertrain systems', *IEEE Control Systems*, Vol. 18, No. 5, pp.17–33.

Pu, J. and Yin, C. (2007) 'Optimal control of fuel economy in parallel hybrid electric vehicles', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*.

Puleston, P.F., Monsees, G. and Spurgeon, S.K. (2002) 'Air-fuel ratio and speed control for low emission vehicles based on sliding mode techniques', *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*.

Rachid, A., Liazid, A. and Champussin, J.C. (1994) 'Nonlinear modelling of a turbocharged diesel engine', *Proceedings of the IEEE Control Applications*, Vol. 1, pp.133–136, Piscataway.

Rakha, H. and Ahn, K. (2004) 'Integration modelling framework for estimating mobile source emissions', *Journal of Transportation Engineering*, Vol. 130, No. 2, pp.183–193.

Rakha, H. and Van Aerde, M. (2000) 'Requirements for evaluating traffic signal control impacts on energy and emissions based on instantaneous speed and acceleration measurements', *Transportation Research Record: Journal of the Transportation Research Board*, No. 1738, pp.56–67.

Rakha, H., Lucic, I., Henrique, S. and Setti, J.R. (1999) 'Vehicle dynamics model for predicting maximum truck acceleration levels', Transportation Research Report, Virginia Polytechnic Institute and State University.

Rakha, H., Van Aerde, M., Bloomberg, L. and Huang, X. (1998) 'Construction and calibration of a large-scale micro-simulation model of the Salt Lake area', Research Report, Center for Transportation Research Virginia Polytechnic Institute & State University.

Rakha, H.A., Ahn, K., Faris, W. and Moran, K. (2010) 'Simple vehicle powertrain model for use in traffic simulation software', *89th Transportation Research Board Annual Meeting*.

Rakha, H.A., Ahn, K., Moran, K., Saerens, B. and Van den Bulck, E. (2011) 'Simple comprehensive fuel consumption and CO_2 emission model based on instantaneous vehicle power', *Proceedings of the 90th Transportation Research Board Annual Meeting*, USA.

Rakopoulos, C.D., Rakopoulos, D.C. and Kyritsis, D.C. (2003) 'Development and validation of a comprehensive two-zone model for combustion and emissions formation in a DI diesel engine', *International Journal of Energy Research*, Vol. 27, No. 14, pp.1221–1249.

Rakotomamonjy, A., Le Riche, R., Gualandris, D. and Harchaoui, Z. (2007) 'A comparison of statistical learning approaches for engine torque estimation', *Control Engineering Practice*, Vol. 16, No. 1, pp.43–55.

Ran, H., Thomas, R. and Mavris, D. (2007) 'A mean value based sizing and simulation model of a hydrogen fueled spark-ignition internal combustion engine', *Proceedings of the Society of Automotive Engineers SAE 2007 AeroTech Congress & Exhibition*, USA, paper # 2007-01-3789.

Reitz, R.D. and Rutland, C.J. (1992) *Three-Dimensional Modelling of Diesel Engine Intake Flow, Combustion and Emissions – II*, USA National Aeronautics And Space Administration (NASA), Lewis Research Center, Research Report # DOE/NASA/1087-2, NASA CR-191189.

Rhodes, D.B. and Keck, J.C. (1985) 'Laminar burning speed measurements of Indolene-air-Diluent mixtures at high pressures and temperature', *SAE Transactions*, Vol. 94, SAE International, paper # 850047.

Richardson, A.J. and Akcelik, R. (1981) 'Fuel consumption models and data needs for the design and evaluation of urban traffic system', *Australian Road Research Board*.

Rizzoni, G. (1989) 'A stochastic model for the indicated pressure process and the dynamics of the internal combustion engine', *IEEE Transactions on Vehicular Technology*, Vol. 38, No. 3, pp.180–192.

Rizzoni, G. and Guzzella, L. and Baumann, B.M. (1999) 'Unified modelling of hybrid electric vehicle drivetrains', *IEEE/ASME Transactions of Mechatronics*, Vol. 4, No. 3, pp.246–257.

Rizzotto, G., Lo Presti, M., Di Marco, F. and Lanzafame, R. (1995) 'Road vehicle energy consumption model by using neuro-fuzzy approach', *Proceedings of the IEEE 1995 International Symposium on Industrial Electronics (ISIE '95)*, Vol. 2, pp.798–802.

Rothery, R.W. (1975) 'Chapter 4: car following models, in Gartner, N.H., Messer, C. and Rathi, A.K. (Eds.): *Traffic Flow Theory*, United States Department of Transportation, Federal Highway Administration.

Roy, S. and Liu, Z. (2008) 'Road vehicle suspension and performance evaluation using a two-dimensional vehicle model', *International Journal of Vehicle Systems Modelling and Testing*, Vol. 3, Nos. 1/2, pp.68–93.

Şahin, Z. and Durgun, O. (2008) 'Multi-zone combustion modelling for the prediction of diesel engine cycles and engine performance parameters', *Applied Thermal Engineering*, Vol. 28, Nos. 17–18, pp.2245–2256.

Schmitt, J., Fremovici, M., Grondin, O. and Le Berr, F. (2009) 'Compression ignition engine model supporting powertrain development', *Proceedings of the IFAC Workshop on Engine and Powertrain Control, Simulation and Modelling, Engine and Powertrain Control, Simulation and Modelling*, France.

Sciarretta, A., Back, M. and Guzzella, L. (2004) 'Optimal control of parallel hybrid electric vehicles', *IEEE Transactions on Control Systems Technology*, Vol. 12, No. 3, pp.352–363.

Scillieri, J.J., Buckland, J.H. and Freudenberg, J.S. (2005) 'Reference feedforward in the idle speed control of a direct-injection spark-ignition engine', *IEEE Transactions on Vehicular Technology*, Vol. 54, No. 1, pp.51–61.

Seykens, X.L.J., Baert, R.S.G., Willems, F.P.T., Vink, W. and Van den Heuvel, I.T.M. (2006) 'Development of a dynamic engine brake model for control purposes', *Proceedings of the New Trends in Engine Control, Simulation and Modelling Conference*, France.

Shaver, G.M., Roelle, M.J. and Gerdes, J.C. (2006) 'Modelling cycle-to-cycle dynamics and mode transition in HCCI engines with variable valve actuation', *Control Engineering Practice*, Vol. 14, No. 3, pp.213–222.

Sher, E., Ben-Ya'ish, J. and Kravchik, T. (1992) 'On the birth of the spark channel', *Combustion and Flame*, Vol. 89, pp.186–194.

Shiao, Y., Pan, C. and Moskwa, J.J. (1994) 'Advanced dynamic spark ignition engine modelling for diagnostics and control', *International Journal of Vehicle Design*, Vol. 15, No. 6, pp.578–596.

Shrivastava, R., Hessel, R. and Reitz, R.D. (2002) 'CFD optimization of DI diesel engine performance and emissions using variable intake valve actuation with boost pressure, EGR and multiple injections', *SAE 2002 World Congress & Exhibition*, March, Detroit, MI, USA, paper # 2002-01-0959.

Shyani, R.G. and Caton, J.A. (2009) 'A thermodynamic analysis of the use of exhaust gas recirculation in spark ignition engines including the second law of thermodynamics', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 223, No. 1.

Silverlind, D. (2001) 'Mean value engine modelling with modelica', Master thesis, Linköpings Universitet, Sweden.

Sim, H. and Sunwoo, M. (2004) 'Development and validation of a dynamic model for a gaseous-fuel engine', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*.

Smit, R. and McBroom, J. (2009) 'Development of a new high resolution traffic emissions and fuel consumption model', *Road and Transport Research*, Vol. 18, No. 4, pp.3–13.

Smit, R., Brown, A.L. and Chan, Y.C. (2008) 'Do air pollution emissions and fuel consumption models for roadways include the effects of congestion in the roadway traffic flow?', *Environmental Modelling & Software*, Vol. 23, Nos. 10–11, pp.1262–1270.

Smit, R., Smokers, R. and Rabe, E. (2007) 'A new modelling approach for road traffic emissions: VERSIT+', *Transportation Research Part D: Transport and Environment*, Vol. 12, No. 6, pp.414–422.

Sommer, C., German, R. and Dressler, F. (2011) 'Bidirectionally coupled network and road traffic simulation for improved IVC analysis', *IEEE Transactions on Mobile Computing*, Vol. 10, No. 1, pp.3–15.

Song, G., Yu, L. and Wang, Z. (2009) 'Aggregate fuel consumption model of light-duty vehicles for evaluating effectiveness of traffic management strategies on fuels', *Journal of Transportation Engineering*, Vol. 135, No. 9, pp.611–618.

Sorenson, S.C., Hendrick, E., Magnusson, S. and Bertelsen, A. (2005) 'Compact and accurate turbocharger modelling for engine control', *Electronic Engine Controls, SAE Special Collections 2005 (SP-1975)*, SAE International, paper # 2005-01-1942.

Souder, J.S. (2002) 'Powertrain modelling and nonlinear fuel control', MSc thesis, University of California, Berkley.

Sridhar, G., Paul, P.J. and Mukunda, H.S. (2006) 'Zero-dimensional modelling of a producer gas-based reciprocating engine', *Proceedings of the IMechE, Part A: J. Power and Energy*, Vol. 220, No. 8, pp.923–931.

Stankovic, A. (2000) 'Modelling of air flows in automotive engines using modelica', Master thesis, Linköping University.

Stefanopoulou, A.B., Kolmanovsky, I. and Freudenberg, J.S. (2000) 'Control of variable geometry turbocharged diesel engines for reduced emissions', *IEEE Transactions on Control System Technology*, Vol. 8, No. 4, pp.733–745.

Streit, E.E. and Borman, G.L. (1971) 'Mathematical simulation of a large turbocharged two-stroke diesel engine', SAE International, paper # 710177.

Sun, J., Kolmanovsky, I., Cook, J.A. and Buckland, J.H. (2005) 'Modelling and control of automotive powertrain systems: a tutorial', *Proceedings of the 2005 American Control Conference*, Portland, USA, paper # ThC14.1, pp.3271–3283.

Sutton, R.W. (2000) 'Investigation of cyclic dispersion under lean fueling and high levels of simulated EGR', MS thesis, University of Missouri-Rolla.

Swan, K., Shahbakhti, M. and Koch, C. (2006) 'Predicting start of combustion using a modified knock integral method for an HCCI engine', *Proceedings of the SAE World Congress*, paper # 2006-01-1086.

Taklanti, A. and Delhaye, B. (1999) 'Multi-dimensional modelling of the aerodynamic and combustion in diesel engines', *Oil & Gas Science and Technology – Rev. IFP*, Vol. 54, No. 2, pp.271–277.

Tapani, A. (2005) 'Versatile model for simulation of rural road traffic', *Transportation Research Record: Journal of the Transportation Research Board*, No. 1934, pp.169–178.

Taylor, N.B. (2003) 'The CONTRAM dynamic traffic assignment model', *Networks and Spatial Economics*, Vol. 3, pp.297–322.

The MathWorks Inc. (2000) *SIMULINK. Dynamic System Simulation for MATLAB, Version 4*, The MathWorks Inc., Natick, MA.

The Seider Group (1997) *MINUTP Technical User's Manual*, The Seider Group, Palo Alto, CA.

The Urban Analysis Group (1992) *TRANPLAN, Version 7.1*, The Urban Analysis Group, Danville, CA.

Tirkey, J.V., Gupta, H.N. and Shukla, S.K. (2010) 'Analytical study to minimize the engine exhaust emissions and safe knock limit of CNG powered four-stroke SI engine', *International Journal of Energy and Environment*, Vol. 1, No. 1, pp.31–52.

United Nations Economic and Social Council (2009) *Major Issues in Transport: Transport and Environment*, United Nations Economic and Social Council.

United States Environmental Protection Agency EPA (1994) *User's Guide to MOBILE 5 (Mobile Source Emission Factor Model)*, Environmental Protection Agency, Ann Arbor, Michigan.

US Department of Transportation (1996) *Key Findings from the Intelligent Transportation Systems (ITS) Program*, Federal Highway Administration (FHWA), Publication No. FHWA-JPO-96-0036.

Varnavas, C. and Assanis, D.N. (1996) 'A high temperature and high pressure evaporation model for the KIVA-3 code', SAE International, paper # 960629.

Verhelst, S. and Sierens, R. (2007) 'A quasi-dimensional model for the power cycle of a hydrogen-fuelled ICE', *International Journal of Hydrogen Energy*, Vol. 32, No. 15, pp.3545–3554.

Wagner, J.R., Dawson, D.M. and Zeyu, L. (2003) 'Nonlinear air-to-fuel ratio and engine speed control for hybrid vehicles', *IEEE Transactions on Vehicular Technology*, Vol. 52, No. 1, pp.184–195.

Wagner, R.M., Daw, C.S. and Green, J.B. (2001) 'Low-order map approximations of lean cyclic dispersion in premixed spark ignition engines', SAE International, paper # 2001-01-3559.

Wahlstrom, J. (2005) 'Modelling of a diesel engine with VGT and EGR', Technical report, Division of Vehicular Systems, Linkoping University, Linkoping, Sweden.

Wahlstrom, J. (2009) 'Control of EGR and VGT for emission control and pumping work minimization in diesel engines', PhD thesis, Linkoping University, Sweden.

Wang, H. and Zhang, J. (2006) 'Control oriented dynamic modelling of a turbocharged diesel engine', *Proceedings of the Sixth International Conference on Intelligent Systems Design and Applications (ISDA'06)*.

Wang, H., Fu, L., Zhou, Y. and Li, H. (2008) 'Modelling of the fuel consumption for passenger cars regarding driving characteristics', *Transportation Research Part D: Transport and Environment*, Vol. 13, No. 7, pp.479–482.

Watson, H.C. and Milkins, E.E. (1980) 'A simplified method for quantifying fuel consumption of vehicles in urban traffic', *SAE-Austria*, Vol. 40, No. 1, pp.6–13.

Watson, N. (1984) 'Dynamic turbocharged diesel engine simulator for electronic control system development', *Journal of Dynamic Systems, Measurements, and Control*, Vol. 106, No. 1, pp.27–45.

Watson, N., Pilley, A.D. and Marzouk, M. (1980) 'A combustion correlation for diesel engine simulation', SAE International, paper # 800029.

Weeks, R.W. and Moskwa, J.J. (1995) 'Automotive engine modelling for real-time control using MATLAB/SIMULINK', *Proceedings of SAE 1995 International Congress and Exposition*.

Wei, X. and Rizzoni, G. (2001) 'A scalable approach for energy converter modelling and supervisory control design', *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, pp.1281–1288.

Whitehouse, N. and Sareen, B.K. (1974) 'Prediction of heat release in a quiescent chamber diesel engine allowing for fuel/air mixing', SAE International, paper # 740084.

Winge Vigild, C. (2001) 'The internal combustion engine –modelling, estimation and control issues', PhD thesis, Technical University of Denmark.

Winterbone, D.E., Thiruarooran, C. and Wellstead, P.E. (1977) 'A wholly dynamic model of a turbocharged diesel engine for transfer function evaluation', SAE International, paper # 770124.

Wirth, M., Keller, P. and Peters, N. (1993) 'A flamelet model for premixed turbulent combustion in SI engines', SAE International, paper # 932646.

Wu, H., Aquino, C.F. and Chou, G.L. (1984) 'A 1.6 litre engine and intake manifold dynamic model', ASME, paper # 83-WA/DSL- 39.

Wu, X. and Moin, P. (2008) 'Large-activation-energy theory for premixed combustion under the influence of enthalpy fluctuations in the oncoming mixture part II: applications', *Annual Research Briefs 2008*, pp.421–436, Center for Turbulence Research, Imperial College London.

Xia, H. and Oh, P. (1999) 'A dynamic model for automotive torque converters', *International Journal of Vehicle Design*, Vol. 21, Nos. 4–5, pp.344–354.

Xin, W., Hourdos, J. and Michalopoulos, P. (2008) 'The less-than- perfect driver: a model of collision inclusive car-following behavior', *Transportation Research Record*, No. 2088, pp.126–137.

Yang, M. and Sorenson, S.C. (1992) 'Modelling of the dynamic processes in an electronic diesel fuel injection system', SAE SP, paper # 920240.

Yildiz, Y., Annaswamy, A.M., Yanakiev, D. and Kolmanovsky, I. (2009) *Spark Ignition Engine Idle Speed Control: An Adaptive Control Approach*, MIT Press, Cambridge, Massachusetts, USA.

Yoon, P., Park, S. and Sunwoo, M. (2000) 'A nonlinear dynamic model of SI engines for designing controller', *Proceedings of FISITA World Automotive Congress*.

Yue, H. (2008) 'Mesoscopic fuel consumption and emission modelling', Doctor of Philosophy dissertation, Virginia Polytechnic Institute and State University.

Zallinger, M., Anh, T.L. and Hausberger, S. (2005) 'Improving an instantaneous emission model for passenger cars', *Proceedings of the 14th International Conference on Transport and Air Pollution*, Graz, Austria, pp.167–176.

Zargari, S.A. and Khan, A.M. (2003) 'Fuel consumption model for bus rapid transit', *Journal of Advanced Transportation*, Vol. 37, No. 2, pp.139–157.

Zhao, F.Q., Lai, M.C. and Harrington, D.L. (1997) 'A review of mixture preparation and combustion control strategies for spark-ignited direct injection gasoline engines', SAE International, paper # 970627.

Zhou, P., Zhou, S. and Clelland, D. (2006) 'A modified quasi-dimensional multi-zone combustion model for direct injection diesels', *International Journal of Engine Research*, Vol. 7, No. 4, pp.335–345.

Zito, G. and Doré Landau, I. (2005) 'Narmax model identification of a variable geometry turbocharged diesel engine', *Proceedings of the American Control Conference 2005*, Portland, USA.

Zweiri, Y.H., Whidborne, J.F. and Seneviratne, L.D. (2001) 'Detailed analytical model of a single-cylinder diesel engine in the crank angle domain', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 215, No. 11, pp.1197–1216.

Appendix

Definitions, acronyms, abbreviations

Comprehensive modal emission model

FR	Fuel-use rate in grams/s
$g_{\text{emissions}}/g_{fuel}$	Grams of engine-out emissions per grams of fuel consumed
CPF	The ratio of tailpipe to engine-out emission
P_{tract}	Total tractive power (kw)
A	Coefficient of rolling resistance
B	Coefficient of speed-correction to rolling resistance
C	Coefficient of air-drag factor
v	Instantaneous speed (m/s)
a	Instantaneous acceleration (m/s^2)
g	Gravitational constant (9.81 m/s^2)
θ	The road grade angle
P	The engine power output
η_{tf}	The combined efficiency of the transmission and final drive
P_{acc}	The engine power demand associated with the operation of vehicle accessories, such as air conditioning
k	The engine friction factor
N	Engine speed (rps)
V	Engine displacement (L)
η	A measure of indicated efficiency (≈ 0.4)
Φ	Air/Fuel equivalence ratio
a_{CO}	Emission of CO index coefficient
r_{HC}	Emission of HC residual coefficient
ei	either CO or HC emissions
ε_{ei}	The maximum catalyst CO or HC efficiency
FR	The fuel rate (g/s)
b_{ei}	The stoichiometric CPF coefficients
c_{ei}	The enrichment CPF coefficient

VT-Microscopic model

MOE_e	Instantaneous fuel consumption or emission rate (L/s or mg/s)
v_{VT}	Instantaneous speed of vehicle (km/h)
$k^e_{i,j}$	Vehicle-specific acceleration regression coefficients for MOE_e
$l^e_{i,j}$	Vehicle-specific deceleration regression coefficients for MOE_e

Watson model

F	Fuel consumed (L/km)
Vs	Space mean speed (km/h)
Vf	Final speed (km/h)
Vi	Initial speed (km/h)
Xs	total section length (km)

Elemental model

Φ_E	Fuel consumption per unit distance
T	Average travel time per unit distance
V	Average speed
$K1$	Model parameter represents the vehicle mass (in mL/km)
$K2$	Model parameter that is a function of vehicle average speed (in mL/s)

VeTESS model

F_{total}	The total force acting on the vehicle
F_{accel}	The force required in order to cause an acceleration of the mass of the vehicle
F_{grad}	The component of the weight force of the vehicle acting parallel to the slope
F_{roll}	The rolling resistance
F_{aero}	The aerodynamic resistance