

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

Waleed Faris

International Islamic Univ Malaysia

Hesham Rakha

Virginia Tech

Salah A.M. Elmoselhy

International Islamic Univ. Malaysia

ABSTRACT

Climate change due to greenhouse gas emissions has led to new vehicle emissions standards which in turn have led to a call for vehicle technologies to meet these standards. Modeling of vehicle fuel consumption and emissions emerged as an effective tool to help in developing and assessing such technologies, to help in predicting aggregate vehicle fuel consumption and emissions, and to complement traffic simulation models. The paper identifies the current state of the art on vehicle fuel consumption and emissions modeling and its utilization to test the environmental impact of the Intelligent Transportation Systems (ITS)' measures and to evaluate transportation network improvements. The study presents the relevant models to ITS in the key classifications of models in this research area. It demonstrates that the trends of vehicle fuel consumption and emissions provided by current models generally do satisfactorily replicate field data trends. It shows as well that microscopic modeling is the most accurate type of vehicle fuel consumption and emissions modeling and macroscopic modeling is most helpful in estimating aggregate emissions inventories. In addition, the paper demonstrates that mesoscopic models and empirical models strike a balance between accuracy and simplicity so that they are highly suitable for evaluating the environmental impact of the ITS' measures and transportation network improvements. The study indicates that there is a significant impact of ITS measures on vehicle fuel consumption and emissions rates. It identifies as well the relation among transportation models, cold start excess emission modeling subcategories, and hot-stabilized emission models. The study concludes that no one model as yet fully meets the needs of ITS applications.

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INTRODUCTION

The transportation sector is the third largest consumer of energy, the largest consumer of petroleum products, and one of the greatest contributors to air pollution worldwide [1]. Emissions from vehicles contribute to smog, low visibility, and various greenhouse gas emissions. About half of all air pollution and more than 80 percent of air pollution in cities are produced by the transportation sector worldwide [1]. The transportation sector is the second largest contributor to carbon dioxide emissions [1]. Its energy consumption is growing faster than that of other sectors, driven by the rapid increase in motorization and strong transport demands from

economic development. These facts require the transport sector to take more effective mitigation and adaptation measures in order to reduce energy consumption and emissions. Therefore, automobile manufacturers are currently under pressure to produce more environmentally friendly vehicles [1].

Vehicle fuel consumption and emissions are having great impact on global economy. As the result of auto industries being under increasing pressure from the governments to reduce the expense of energy consumption and emissions, the ITS was introduced. Vehicle fuel consumption and emission models are currently the primary tools for evaluating the

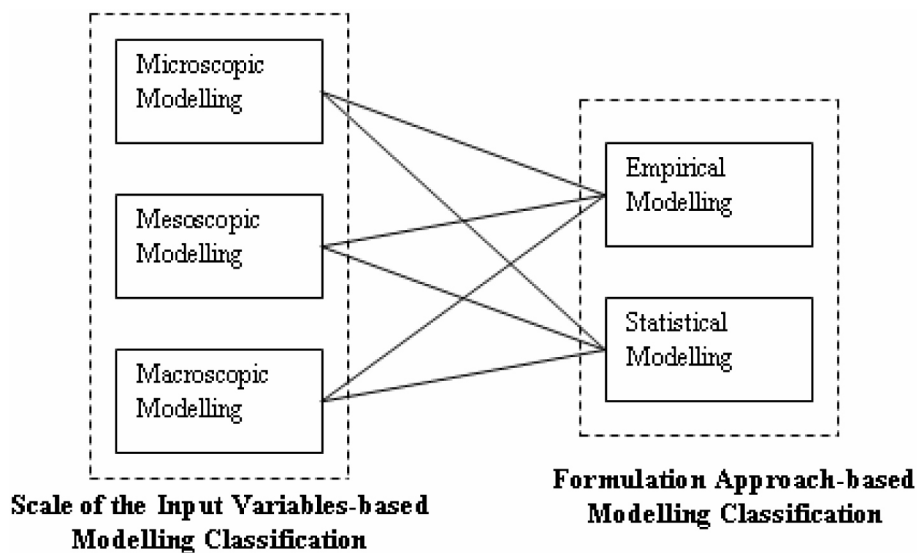


Figure 1. The relation between modeling classifications and subcategories

regional impacts of transportation projects and for evaluating new hardware in the field of ITS. In typical applications, a transportation planning model such as TRANPLAN [2], MINUTP [3], or EMM/2 [4] 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 [5] is used to compute the average fuel consumption and emissions rates for the facility. Within this step, a base emissions rate is first selected for the facility considered. This base emissions rate reflects the fuel consumption and emissions measurements that were gathered in a laboratory using pre-defined test drive cycles. This base rate is then modified to account for the differences in average speeds between the laboratory and real-world cycles. In addition, it is modified to account for the 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 traveled on the facility [6].

Macroscopically, single fuel consumption and emissions rates are produced for each average speed input. These rates are produced under a couple of assumptions: (i) all vehicles pollute similarly for the same average speed and vehicle-miles traveled, (ii) variations in driver behavior can be neglected [7]. 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 issue arises when comparing drive cycles with identical average speeds since identical emission rates would then be estimated for all cycles despite differences in the second-by-second speed profiles. The present paper addresses this issue and its relation to the ITS and reviews the current state of the art on vehicle fuel

consumption and emissions modeling. The paper commences with investigating the key relevant models of vehicle fuel consumption and emissions to ITS through the two key classifications of these models. The relation between vehicle fuel consumption and emissions models and start conditions follows. The impact of ITS measures on vehicle fuel consumption and emissions rates is then presented. The paper concludes with highlighting in the discussion section the key research challenges and future research directions in this research area.

VEHICLE FUEL CONSUMPTION AND EMISSIONS MODELING AND ITS

The research objective of estimating vehicle fuel consumption and emission rates has proved to be interesting enough to inspire researchers to develop more than one approach to modeling. These approaches can be primarily classified into two key categories of classification: (1) scale of the input variables-based modeling, (2) formulation approach-based modeling [8]. Based on the scale of the input variables the current state-of-the-art and current state-of-the-practice models can be divided into three subcategories: microscopic, mesoscopic, and macroscopic models. The subcategories of the formulation approach-based modeling classification in ITS applications are mainly empirical and statistical models. The relation between the subcategories in each of these two classifications is shown in Fig 1.

Figure 1, illustrates that each of the subcategories of the formulation approach-based modeling classification can be applied at micro-scale, meso-scale, or macro-scale depending on the application for which the model. These subcategories help in evaluating the environmental impact of the ITS' measures and in evaluating transportation network

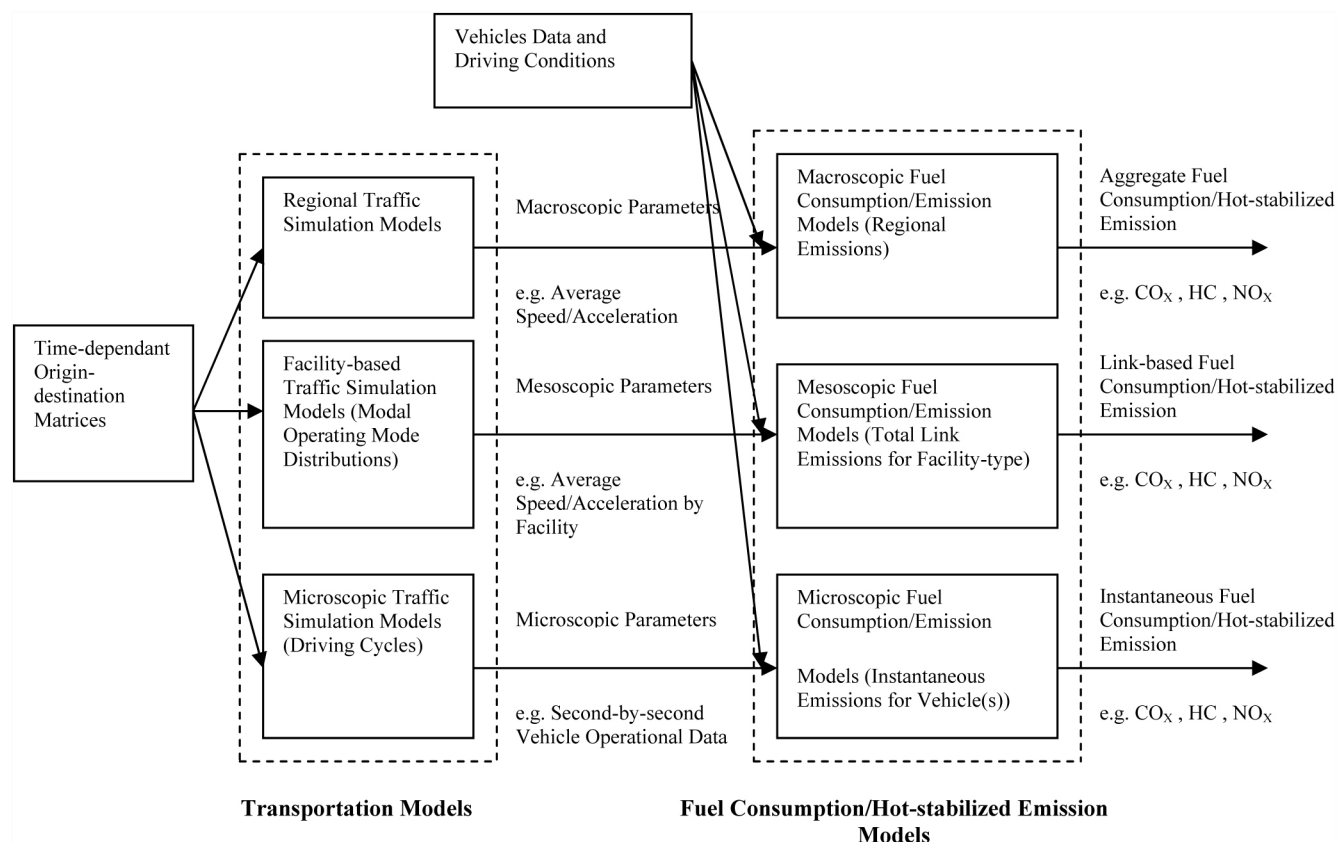


Figure 2. Relation between fuel consumption/hot-stabilized emission modeling subcategories and transportation models

improvements. Basically there are nine integrated components of the ITS: traffic signal control, free way management, transit management, electronic fair payment, electronic toll payment, incident management, traveller information services, emergency management services, and railway grade crossing safety [9]. In another classification of the ITS services, there are seven ITS service bundles: travel and transportation management, public transportation operations, electronic payment, commercial vehicle operations, emergency management, advanced vehicle control and safety systems, and information management. The rapid growth of the ITS applications in recent years is generating an increasing need for tools to help in system design and assessment. Traffic simulation models emerged as an effective tool for traffic control. These traffic simulation models are needed not only for assessing the benefits of ITS in a planning mode but also for generating scenarios, optimizing control, and predicting network behavior at the operational level. There are four main uses of traffic simulation models for ITS: (1) simulating networks to assess a set of transportation control options offline, (2) short term forecasting, (3) enhancing assignment models which are used to predict changes in traffic flows due to policy implementation, (4) providing inputs to car driving simulations in order to allow the assessment of new in-vehicle systems in a cost-effectively safe environment [10].

The relation between the modeling classifications and subcategories presented in the present paper and the ITS lies mainly in the traffic signal control and free way management components of the ITS in terms of traffic simulation models. These two components are among the subcomponents of the travel and transportation management bundle and the advanced vehicle control and safety systems bundle, respectively. The relation between these subcategories and traffic simulation models as a main component of the ITS is depicted in Fig. 2.

Traffic simulation models seem to be one of the useful means of estimating changes in emissions that result from strategies which affect traffic flow. These models can provide a relatively accurate assessment of impacts [10]. As can be gathered from Fig. 2, average speeds from traffic models are estimated from traffic models and are fed into fuel consumption and emission models. The fuel consumption and emission models in turn convert these data into fuel consumption and emission estimates. These estimates are then accumulated to estimate the aggregate fuel consumption and emission at an arterial link, free way, or network-wide scale. The two key classifications of vehicle fuel consumption and emissions modeling will be presented in the following couple of sections.

SCALE OF THE INPUT VARIABLES-BASED MODELING CLASSIFICATION

The subcategories of the scale of the input variables-based modeling are: (1) microscopic models, (2) macroscopic models, (3) mesoscopic models, as suggested by Yue [6]. Microscopic models use instantaneous speed and acceleration data to estimate vehicle fuel consumption and emission rates. The fuel consumption and emissions rates estimated from microscopic models are instantaneous as well. Macroscopic models use aggregate network-based parameters in order to estimate network-wide fuel consumption and emissions rates. Mesoscopic models use a scale that lies in-between the macroscopic scale and microscopic scale [6]. All of these three sub-categories can be called modal models if they account for different standard operating modes. The following three subsections will present these subcategories, respectively.

Microscopic Models

Microscopic models estimate instantaneous vehicle fuel consumption and emission rates that are then aggregated to estimate network-wide measures of effectiveness. Microsimulation models can account for the effects of the variance of driver behavior on emissions. The instantaneous fuel consumption-based models are derived from a relationship between fuel consumption rates and instantaneous vehicle power. Second-by-second vehicle characteristics and road conditions are thus required in order to estimate the fuel consumption rate. Due to the disaggregate characteristics of the fuel consumption data, these models are usually used to evaluate individual transportation projects. The instantaneous fuel consumption-based models can be used in microscopic traffic simulation packages in order to estimate the fuel consumption rate based on instantaneous speeds and accelerations of individual vehicles [6]. Microscopic models help assess new in-vehicle systems in a safe environment by providing for instance instantaneous fuel consumption and emission estimates. In this section, the following models will be considered: (a) key microscopic vehicle fuel consumption and emission models, (b) microscopic mobility and traffic simulation models.

Key Microscopic Vehicle Fuel Consumption and Emissions Models

The key microscopic vehicle fuel consumption and emission models that are relevant to ITS include CMEM, VT-Micro model, PHEM, VERSIT^{micro}, MOVES, and MEF models. This section presents each of these key models highlighting their main features. An et al., [7] developed a modal emissions model, called Comprehensive Modal Emission Model (CMEM), which is based on a simple parameterized empirical approach. The CMEM 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 conducted 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 modeled 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 [6]. The CMEM is capable of doing the following tasks: (1) estimating the second-by-second emissions rates based on network changes that affect the acceleration/deceleration of vehicles in traffic, (2) 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: (i) it does not represent real-world driving conditions since data was collected using a dynamometer, (ii) it is incapable of estimating particulate emissions. Despite these limitations, the CMEM is still among the best modal emissions models [11].

An HDD truck sub-model was developed in the CMEM framework for estimating vehicle fuel consumption and regulated emissions rates for heavy duty diesel vehicles [12]. In this sub-model, a parameterized physical approach is used in which the emission process is broken down into components that correspond to physical phenomena associated with vehicle operation and emission production. This submodel was tested using a variety of trucks taking into consideration the effects of varying grade and the use of variable fuel injection strategies. Overall, the simulation of the sub-model showed good agreement with the experimental measurements with a coefficient of determination of 0.855. However, the simulation of the sub-model for CO emission was of lower accuracy with a coefficient of determination of 0.5776.

The CMEM is adopted in the PARAMICS microscopic traffic simulator, which was originally developed at the Edinburgh Parallel Computing Center in Scotland. It provides the most comprehensive visual display for viewing the results through multiple windows and 3-D animation of vehicle movements. 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 center modeling, 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 can model the interface between drivers and ITS. It provides integrated modeling of networks consist of free ways, arterials, and minor roads, various intersection types (e.g. signals, stop signs, and roundabouts) and parking garages with no limit on the network size, on on

the number of vehicles that can be simulated. The applications of PARAMICS to ITS include ramp meters, loop detectors linked to variable speed signs, VMS and CMS signing strategies, in-vehicle network state display devices, and in-vehicle route guidance. PARAMICS has the advantage of using credible theories and of having the ability to output measures of performance, such as travel times and speeds, outperforming some other microscopic simulators [10]. However, it has certain limitations which include: (1) lack of equilibrium traffic assignment, (2) limited options in modeling traveler 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 modeling incidents and work zones [10].

Rakha and Ahn developed a microscopic vehicle fuel consumption and emission model [13], [14], [15]. This model, which is known as VT-Micro, predicts the instantaneous fuel consumption and emission rates of HC, CO, NO_x and CO₂ of individual vehicles based on their instantaneous speed and acceleration levels. 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 [6]. The model accounts for the accelerating, idling, cruising and decelerating driving modes. This split is implemented in the VT-Micro in order 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 [16], [17], [18]. VT-Micro is able to follow closely the trends in increasing fuel consumption with higher speeds and sharper acceleration. This 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 percent of actual measured field values, surpassing the accuracy of the CMEM's estimates. The VT-Micro model has been incorporated within INTEGRATION, a microscopic traffic simulation package, to further demonstrate its application to traffic engineering and ITS, such as evaluating corridor improvement strategies and assessment of real time route guidance benefits [6], [10]. INTEGRATION appears to have a relatively high probability of success in real world applications [19].

The Passenger car and Heavy duty Emissions Model (PHEM) uses an emission 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, CO₂, HC and NO_x. PHEM can not as yet model microscopically PM emissions precisely. The model provides predictions of aggregate emissions that are less accurate than the predictions of the INTEGRATION model [20], [21].

The PHEM is utilized in the VISSIM which is another microscopic traffic simulator that can be used to simulate integrated networks. It is a time-step and behavior-based simulator that is usually used for transit signal priority and intersection/interchange design and operations. VISSIM can analyze 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, and variable message signs. VISSIM is thus a useful tool for the evaluation of various transport alternatives. The input into the model is time-dependant origin-destination matrices whereas it generates numerous user-customizable output files. The output files include 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. The VISSIM can be utilized in numerous ITS applications including transit signal priority studies, and intersection/interchange design and operations [10]. PARAMICS is better than VISSIM in terms of being tested for real-world applications and of being obtainable by the public. In addition, VISSIM requires relatively significant amount of time to code the input data [10].

The VERSIT^{+micro} was developed in the Netherlands by TNO in order to simulate the traffic emissions of CO₂, NO_x and PM₁₀ as well as energy use factors as outputs. The inputs to the VERSIT^{+micro} are the instantaneous velocity and acceleration of vehicle. The emission factors in this model are differentiated for various vehicle types and traffic situations, and take into account real-world driving conditions. VERSIT^{+micro} is unique in that it yields consistent results on national, regional and local scales placing it at par to some extent with the INTEGRATION model. It can be used for investigating national greenhouse gas 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. The VERSIT^{+micro} model has been hence chosen to be incorporated officially into the ITS of Japan [22]. Using advanced statistical modeling techniques, VERSIT^{+micro} finds the best fitting emission factor equation for any given driving pattern. It thus makes emission prediction for road traffic (trucks, buses, passenger cars, and motorcycles) helping decision makers to make well-informed vehicle technology incentives. VERSIT^{+micro} 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+^{micro} 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 [23].

The VERSIT+^{micro} is incorporated into the AIMSUN traffic simulator. As an efficient traffic simulator to simulate urban and interurban traffic networks containing a wide range of ITS applications, AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks) emerged to provide the user with a user-friendly interface. It facilitates 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 pros of this model include: user friendly interface, the ability to deal with different traffic networks, and the ability to model different types of traffic control. Its main weakness is that the information or signalization to implement route guidance must come from an external system. The ITS applications of the AIMSUN include traffic control systems, route guidance devices such as VMS, and evaluation of roadway design alternatives. By making more calibration and validation, AIMSUN can be brought to the forefront of micro-simulators to be comparable with VT-Micro [10].

Motor Vehicle Emission Simulator (MOVES) is an emission model and simulator that was developed by the US Environmental Protection Agency (EPA) and is currently adopted officially in the US for vehicle fuel consumption and emission rates evaluation [24]. The current version of MOVES is MOVES2010. The inputs into this model are the vehicle instantaneous speed and acceleration and the output of this model is the rate of emission components that include NO_x, PM, CO, CO₂, SO₂, and NH₃. The MOVES 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 emission factors [25]. Albeit its good estimation of vehicle fuel consumption and emission rates, MOVES is relatively time-consuming. Although MOVES is based on vehicle instantaneous speed and acceleration, EPA utilizes it in order to model emissions from the micro to the macro level maintaining consistency across the scales [26].

Microscopic Emission (HC, CO, NO_x, and CO₂) and Fuel consumption (MEF) models were developed for light-duty vehicles [27]. The key inputs to the MEF are vehicle acceleration and speed. The outputs of the MEF are the emission and fuel consumption rates. The MEF models estimate fuel consumption and CO exhaust emission rates with 9% and 10% accuracy, respectively. However, the accuracy of NO_x exhaust emission rate estimation is relatively lower with 19% accuracy. Both instantaneous

validation and aggregate validation were performed to verify the prediction accuracy of the MEF models and both proved that the MEF models give estimations of emissions and fuel consumption rates more accurate than VT-Micro for light duty vehicles. The MEF models are limited to the specific dataset on the selected vehicles in the study so that they need recalibration for any other dataset. Having presented these key microscopic models, let us now explore the relation between microscopic mobility and traffic simulation models.

Microscopic Mobility and Traffic Simulation Models

Microscopic modeling is highly applicable to mobility applications and traffic simulation. This is apparent in literature, such as what was proposed by Spyropoulou, and Karlaftis, [28], Toledo et al., [29], Ahmed [30], and Rakha, and Crowther, [31]. Spyropoulou, and Karlaftis, [28] presented the Gipps' car-following model that was developed by Gipps, as a behavioral car-following, discrete-time, continuous space, and microscopic traffic model. The model was originally developed for simulation of free flow traffic in order to assess the effect of the system on travel time, fuel consumption and traffic emissions. Yet, Gipps' model is currently used as well in various traffic simulation programs including MULTSIM [32], [33], SIGSIM [34], AIMSUN, DRACULA and SITRAS. However, when the simulated vehicle does not expect a sudden or rapid deceleration from the preceding one, Gipps's model becomes unsuitable and Mauro's model for vehicle behavior simulation is used [35], [36].

Toledo et al., [29] developed an integrated driving behavior model, which captures both lane changing and acceleration behaviors. In that model, Toledo et al., identified the inter-dependencies between lane changing and acceleration behaviors. Although this model is relatively accurate and highly relevant to road traffic, its calibration for a large-scale network is an extensively time consuming task.

Ahmed, [30] developed models for drivers' acceleration and lane changing behavior. The acceleration model defines two regimes of traffic flow: the car-following regime and the free-flow regime. The lane changing decision process is modeled as a sequence of three steps: decision to consider a lane change, choice of a target lane, and gap acceptance. These models were validated using actual traffic data and a microscopic traffic simulator. Although this model is highly relevant to road traffic, it is very labour intensive in conducting inventory analysis and needs very detailed information which may not be available.

Rakha, and Crowther, [31] compared three state-of-practice steady state car-following microscopic models: the Greenshields model, the Pipes model, and a model that amalgamates both the Greenshields and Pipes models called 'INTEGRATION.' They reported that the Pipes model is implemented in a number of microscopic traffic simulation software, such as the CORSIM. The study concludes that the additional degree-of-freedom in the INTEGRATION model