March 21-23, 2013

DOUBLETREE HOTEL
ANNAPOLIS, MARYLAND

Proceedings of the 54th Annual Transportation Research Forum

TRF

www.trforum.org

MODELING FUEL CONSUMPTION AND EMISSIONS AT SIGNALIZED INTERSECTION APPROACHES: A SYNTHESIS OF DATA SOURCES AND ANALYSIS TOOLS

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ABSTRACT

The continuous growth in demand of vehicular traffic has led to a large increase in fuel consumption and emissions, negatively impacting the environment, public health, and the economy. The main goal of this paper is to synthesize and document the state-of-the-practice in modeling fuel consumption and emissions at signalized intersection approaches. The synthesis work presented in this paper focuses on two main areas: fuel consumption and emission modeling tools for signalized intersection approaches and the sources of emissions inventory and data used in the models. The first part of this paper includes a background covering different traffic-related pollutants, emission factors and different methods used to obtain them and examples of the currently available emission inventories. In the second part, a review of currently available fuel consumption and emission models suitable for modeling traffic operations at signalized intersection approaches is presented covering three different analysis levels: microscopic, mesoscopic, and macroscopic.

1.0 INTRODUCTION

The main goal of this paper is to synthesize and document the state-of-the-practice in modeling fuel consumption and emissions at signalized intersection approaches. It is divided into two main sections: the first focuses on sources of vehicle emissions and fuel consumption data and the second addresses vehicle emissions and fuel consumption modeling capabilities of different signalized intersection simulation modeling tool covering three analysis levels: microscopic, mesoscopic, and macroscopic. For each of the models presented in the paper, details on how both the kinematics and kinetics components of vehicle motion are being represented and modeled will be presented and discussed.

2.0 SOURCES OF VEHICLE EMISSIONS AND FUEL CONSUMPTION DATA

2.1 Emission Inventories

An Emission inventory is a "database that lists, by source, the amount of air pollutants discharged into the atmosphere during a given time period from a certain activity." It is an important component in the air quality management process and is used to determine sources and quantities of different air pollutants and to build emission trends over time ("EPA - Air Quality Management (AQM) - Emissions Inventory" 2012). Some of the methods of collecting vehicle emissions and fuel consumption data to build emission inventories include: 1) continuous monitoring of actual emissions measurements, 2) extrapolating the results from short-term source emissions tests, and 3) merging available activity levels data with associated emission factors.

An emission factor is defined as a value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Emission factors are typically expressed as the weight of a specific pollutant divided by the unit weight, volume, distance, or duration of the activity emitting the pollutant. (Office of Air Quality Planning and Standards 2012c).The general equation for emissions estimations is:

$$E = A * EF * (1 - ER/100) \qquad \text{Equation 1}$$

Where:

- E = emissions;
- A = activity rate;
- EF = emission factor, and
- ER =overall emission reduction efficiency, %

There are several emission factors' databases. An example is the Emission Factors (EMFAC) database that includes emission rates from different types of motor vehicles (passenger cars and heavy-duty trucks) operating on highways, freeways and local roads in California. EMFAC-2011 is the most recent version of this model. Data from 25 million registered vehicles in the 2009 vehicles registration data was used to update the populations in each vehicle class for 59 geographical areas. Travel activity data are provided by regional transportation planning agencies while Vehicle Miles of Travel (VMT) and speed data are obtained from the southern California association of governments, Bay area Metropolitan transportation commission, San Diego association of governments, and san Joaquin valley councils of government (California Environmental Protection Agency - Air Resources Board 2011).

Another extensive source for emissions factors is the EPA's Air Pollutant (AP)-42 Documentation. This documentation was developed by the Emission Factor and Inventory Group (EFIG). It addresses ozone related pollutants (like total organic compounds, oxides of nitrogen, and carbon monoxide), hazardous pollutants, and global warming gases. (Office of Air Quality Planning and Standards 2012c), and ("Compilation of Air Pollutant Emission Factors | Modeling and Inventories | US EPA" 2013)

Examples of emission inventories and their available resources are:

- **National Emission Inventory (NEI):** NEI is a comprehensive and detailed estimate of air emissions and hazardous air pollutants from all air emissions sources. It is developed and maintained by the U.S. Environmental Protection Agency (EPA). NEI is updated every three years based on emission estimates and emission model inputs provided by state, local and tribal air quality agencies form sources in their jurisdictions. The database is supplemented by data developed by the US EPA. ("EPA - Air Quality Management (AQM) - Emissions Inventory" 2012), and (Office of Air Quality Planning and Standards 2012a).
- **EPA Clearinghouse for Inventories & Emission Factors:** This database contains information on emissions inventories, emissions factors, software and tools used for emissions inventories, and emissions modeling. All emission inventory data, tools, and resources could be downloaded from this following source: (EPA 2012)
- **Biogenic Emissions Inventory System (BEIS):** The Biogenic emission sources are emissions that come from natural sources, and need to be accounted for in photochemical grid models, as most types are widespread and ubiquitous contributors to background air chemistry. Often only the emissions from vegetation and soils are included, but other relevant sources include volcanic emissions, lightning, and sea salt. Biogenic emissions are typically computed using a model which utilizes spatial information on vegetation and land use and environmental conditions of temperature and solar radiation. The model inputs are typically horizontally allocated (gridded) data, and the outputs are gridded biogenic emissions which can then be speciated and utilized as input to photochemical grid models. (Office of Air Quality Planning and Standards 2012d).
- **Emissions Modeling System for Hazardous Pollutants (EMS-HAP):** The Emissions Modeling System for Hazardous Pollutants (EMS-HAP) is an emissions processor that performs the steps needed to process an emission inventory for input into the ASPENmodel or the ISCST3 model. EMS-HAP is written in the SAS programming language and is designed to run on any UNIX workstation. The user will need a SAS license and some knowledge of SAS to use this program. ("Related Programs | TTN - Support Center for Regulatory Atmospheric Modeling | US EPA" 2012)
- **NONROAD Vehicle & Engine Emission Modeling:** The NONROAD Model is intended for Windows 98 and later. Its primary use is for estimation of air pollution inventories by professional mobile source modelers, such as state air quality officials and consultants. NONROAD2008 updates NONROAD2005 to include new nonroad emission standards promulgated in 2008 related to small gasoline engines and pleasure craft. (EPA - nonroad 2012)
- **Sparse Matrix Operator Kernel Emissions (SMOKE):** It is a Linux software supported by the "Center for Environmental Modeling for Policy Development (CEMPD)"at the University of North Carolina at Chapel Hill. SMOKE is an active open-source development project supported and distributed through the Community Modeling and Analysis System Center. All required information could be obtained from this following source (SMOKE Version 3.1 2012).
- **International Vehicle Emissions (IVE) Model**: The International Vehicle Emissions (IVE) Model is a computer model designed to estimate emissions from motor vehicles. The model is intended to help cities and regions develop emissions estimates to: focus control strategies and transportation planning on those that are most effective; predict how different strategies will effect local emissions; and measure progress in reducing emissions over time. The model makes estimates of local air pollutants (criteria pollutants), greenhouse gas emissions, and toxic pollutants. (The International Vehicle Emissions (IVE) Model 2012).
- **Comprehensive Modal Emissions Model (CMEM):** CMEM is a microscopic emission rate database. The model is based on a total of 315 vehicle tests in the first phase and another 31 additional tests in subsequent phases (M. J. Barth et al. 2000). CMEM uses a physical, power-demand modal modeling approach based on the vehicle physical characteristics to generate emission tables. The vehicle emissions testing procedure was based on a second-by-second performance with pre- and post-catalyst measurements of CO_2, CO, HC, and NO_x over three separate driving cycles. These driving cycles are the full 3-bag FTP, EPA's SFTP Bag 4 cycles (US06), and a newly designed modal test cycle (MEC01) that focuses on specific modal events. The complete modal emissions model is composed of six

modules which are: 1) engine power demand; 2) engine speed; 3) fuel/air ratio; 4) fuel-rate; 5) engine-out emissions; and 6) catalyst pass fraction (M. J. Barth et al. 2000).

- **Emission Inventory Guidebook:** This emission inventory is prepared by the United Nations European Environment Agency (EEA), and the Task Force on Emissions Inventories and Projections (TFEIP). This guidebook provides a comprehensive guide to state-of-the-art atmospheric emissions inventory methodology. The guidebook also supports the efforts of reporting under the United Nations Economic Commission for Europe (UNECE) Convention on Long- Range Trans-boundary Air Pollution and the European Union (EU) directive on national emission ceilings. (United Nations Economic Commission for Europe 2012), and (TFEIP 2012).

3.0 VEHICLE EMISSIONS AND FUEL CONSUMPTION MODELING CAPABILITIES OF SIMULATION MODELING TOOLS

In this part of the report, different simulation modeling tools are presented. Traffic simulation models could be divided, based on the level of analysis into these three categories:(microscopic, mesoscopic, and macroscopic) (Yue 2008). In the following sections, a brief summary of the characteristics of different models, as they relate to modeling fuel consumption and vehicle emissions at signalized intersection approached will be presented and discussed. The reviews presented include the model's emission modeling capabilities, how vehicle kinematics and kinetics are being represented in the model, and how it could be used for researches related to emissions and fuel consumption.

3.1 Microscopic Simulation Models

Microscopic simulation tools model the movement of individual vehicles on the basis of car-following and lane-changing theories. They describe both the system entities and their interactions at a high level of detail. These models are also designed for operations analyses of systems of road facilities (Lieberman and Rathi 1997), (Dowling, Holland, and Huang 2002), and (Alexiadis, Jeannotte,, and Chandra 2004). Using instantaneous speeds and acceleration of individual vehicles, microscopic models can calculate fuel consumptions. These models are usually used to evaluate individual transportation projects. There are several microscopic simulation models currently available. Examples of these models include: Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (AIMSUN2), Corridor Simulation (CORSIM), INTEGRATION, MICSTRAN (Microscopic Simulator Model for Traffic Networks (MicroSim), Microscopic Traffic Simulator (MITSIM), Probabilistic Adaptive Simulation Model (PADSIM), PARAMICS, SimTraffic, VISSIM, and Wide Area Traffic Simulation (WATSim).

3.1.1 VISSIM

VISSIM is a stochastic, microscopic, time step, and behavior based traffic simulator. VISSIM's traffic model is based mainly on the psychophysical driver behavior model of R. Wiedemann, in which the driver's reactions are in response to the relative speed and distance of the preceding vehicle. VISSIM can simulate multi-modal traffic flows including passenger cars, buses, light rail, trucks, pedestrians, and others. VISSIM was originally developed at the University of Karlsruhe, Germany in the early 1970s, while the commercial distribution, development, and maintenance was started in 1993 by PTV Transworld AG and is still done by them today. (L. Bloomberg and Dale 2000), and (Gomes, May, and Horowitz 2004).

VISSIM is formed mainly from two main parts; the first one is the simulator generator part, in which the user can import aerial photos and schematic drawings and can begin to graphically build the simulation network. The second main part is the signal state generator (SSG), in which the logic of the signal control exists, and in which the user can define lots of different signal operations like fixed time, and ramp metering. (L. Bloomberg and Dale 2000), and (Gomes, May, and Horowitz 2004).

VISSIM was used in several of the research work related to the emissions.This paper is just an example for that. (Umedu, Togashi, and Higashino 2012) proposed a real-time signal control method to minimize CO_2 emissions. This method integrates arrival times from information that consists of position and speed from vehicle to vehicle and vehicle to infrastructure communications. The paper speculates that the more signals that are controlled together the more efficient control can be and thus the authors have decided to use this speculation in their system. The process of analyzing emission was use of mathematic calculation of exhaust output and VISSIM simulation to provide travel times of a corridor.

VISSIM is supporting an add-on called EnViVer. Using the vehicle record data, EnViVer can calculate different types of emissions like CO_2, NO_x, and PM_{10}. The used emission model in EnViVer is the microscopic exhaust gas/emission model VERSIT+ by TNO which is based on emission measurements for about 2,800 vehicles under different driving conditions. The main idea of EnViver is based on importing the PTV VISSIM record files and then calculating the emissions at spatial detail, and finally getting the output tabulated or graphed (PTV Group 2012).

3.1.2 CORSIM

CORSIM is a microscopic simulation program developed by the Federal Highway Administration (FHWA), and part of the Traffic Software Integrated System (TSIS) which offers a windows-based interface for running the model. CORSIM mainly includes two traffic simulation predecessor models, NETSIM and FRESIM. NETSIM is concerned with arterials with at grade intersections (urban street traffic); while FRESIM is modeling uninterrupted facilities including interstate freeways and grade separated expressways (freeway traffic). CORSIM executes the simulation and gets back the network efficiency to the user in predetermined Measures Of Effectiveness (MOEs) .(Minnesota Department of Transportation 2008), (Loren Bloomberg and Dale 2000) , (Park, Yun, and Choi 2004) , (Hall, Darter, and Rexroad 1993).

Unless CORSIM is not able to optimize phase plans, with combining NETSIM and FRESIM models, CORSIM is capable of simulating large set of systems including freeways, urban streets, corridor or networks, different intersection control (e.g. pre-timed signals and actuated ones), almost any surface geometry including turn pockets and number of lanes, weaving sections, work-zones, and bus operations. (Minnesota Department of Transportation 2008), (Loren Bloomberg and Dale 2000), (Park, Yun, and Choi 2004), (Hall, Darter, and Rexroad 1993), and (Peter Holm et al. 2007).

CORSIM is mainly based on link-node structure network model, where links characterize roadway segments, and nodes represent intersections, entry and exit points. (Minnesota Department of Transportation 2008), and (Park, Yun, and Choi 2004). CORSIM is a stochastic simulation model, which means that it utilizes random processes to model drivers' behavior, vehicles characteristics, and interactions into each run. This will lead to the conclusion that many runs may be required to get a true picture for the network, and drawing conclusions based on only one run might be not representative. (Hall, Darter, and Rexroad 1993), (Minnesota Department of Transportation 2008), and (Peter Holm et al. 2007). CORSIM creates tabulated data for fuel consumption and environmental emissions. It can also tabulate and graph the effect of traffic different control strategies on acceleration and fuel consumption. Because CORSIM's data was not updated for many years, FHWA recommends using the data for comparison analysis only, and not as absolute indications (FHWA 2010).

The newer versions of CORSIM have adopted the Vehicle Transient Emissions Simulation Software (VeTESS) for the process of calculating fuel consumption and emissions. VeTESS was developed as a vehicle level tool for the simulation of fuel consumption and emissions for real traffic transient vehicle operation within the EU 5th framework project DECADE (2001-2003). VeTESS is capable of calculating emissions and fuel consumption made by a single vehicle during a defined 'drive-cycle'. For a given driving cycle, VeTESS uses simple mathematical calculations to determine the engine's operating conditions from the force on the vehicle. These calculations involve gear ratios and their efficiencies. Using the equation of motion, Equation 2, VeTESS calculates the total force on the vehicle.

$$F_{total} = F_{accel} + F_{grad} + F_{roll} + F_{aero} \qquad \text{Equation 2}$$

Where:

- 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

The force required to overcome the motion resistances is provided by the engine as a torque. After that, driven wheels convert this torque from rotational to linear motion. 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 (Beckx et al. 2007).

CORSIM was used in many research work related to emissions. This is one example for this type of research. (Kosman et al. 2003) evaluated both CORSIM and VISSIM for project-level emission modeling. This studied project-levels included the impacts of traffic flow improvements resulting from changes in signal timing or other roadway improvements. CORSIM was compared to VISSIM for two different scenarios. In the first scenario, outputs from the two models were compared to spot speed and average speed data collected from the field. In the second scenario, the models' predicted emission reductions were compared to three Congestion Mitigation and Air Quality (CMAQ) projects. Regarding the results of the first scenario, it was found that both CORSIM and VISSIM under-predicted the mid-block spot speed, with a mixed results for average speed. Overall predicted emissions (VOC and NOx) in the first scenario by results from CORSIM, VISSIM, and the field studies were less than 7%. In the second scenario, it was found that CORSIM predictions differences in pre- and post-project speeds are greater than VISSIM predictions for all three projects. This resulted in causing greater reductions in emissions.

3.1.3 CMEM

The Comprehensive Modal Emissions Model (CMEM) is published by the Center for Environmental Research and Technology (CE-CERT) in Riverside California. Development began in the late 1990's with support from the Cooperative Highway Research council, and continued until the final phase was completed in 2005. CE-CERT has also received some support from the Environmental Protection Agency (EPA). CMEM is not a traffic simulator, which means that all vehicle activity data must come from another source. Because of this, microscopic traffic simulation software is often used to generate traffic network and activity data, and input to CMEM to calculate emissions. Several interface applications used to link CMEM with microscopic simulation software have been developed and used with success (Barth et al. 2005). CMEM is an open source, and is available free for download.

CMEM is based on a deterministic physical power demand model, with rates dependent on causal variables such as fuel delivery system, inspection maintenance effects, and vehicle age. Second-by-second vehicle tailpipe emissions are modeled as the product of three components: fuel rate (FR), engine-out emission indices ($g_{emission}/g_{fuel}$), and time dependent catalyst pass fraction (Barth et al. 2000). Because the rates contained in CMEM are based on physical parameters, in theory it could be adapted to represent new vehicle technologies. However, the most recent major changes the CMEM emission rate database took place in 2005, which indicates that the emissions data contained in this software is somewhat outdated.

Because it was desired that CMEM data properly incorporate the physical variables that contribute to emission rates, existing emission inventories were deemed too generalized by vehicle category and not detailed enough for this purpose. Instead, emission rates were developed "in-house" from tests conducted on several hundred recruited vehicles at the University of California Riverside Center for Environmental Research and Technology. CMEM is basically based on a simple parameterized physical approach. It has six modules that predict engine power, engine speed, air/fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction. All emission data used in CMEM was collected in the USA, mostly at the Riverside facility. For the most part, emission data was collected on dynamometer tests, using a number of different drive cycles with the intent to capture the full range of operation in the resulting emission rates. Much of the data used in CMEM was collected before 1998, with additional low emitting vehicle data collected in 2002-2003 (M. Barth et al. 2006). The input operating variables in CMEM model is having some variables. These variables are (acceleration, air/fuel equivalence ratio, and fuel rate), second-by-second speed, road grade angle, and accessory use (such as air conditioning). the main output for this model is the instantaneous emission. This instantaneous emission could be calculated 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 (An et al. 1997). The instantaneous emissions equation is shown in Equation 3.

$$\text{Tailpipe emissions} = \text{FR.}\left(\frac{g_{emission}}{g_{fuel}}\right).CPF \qquad \text{Equation 3}$$

Where:

FR = fuel-use rate in grams/s;

$g_{emissions}/g_{fuel}$ = grams of engine-out emissions per grams of fuel consumed; and

CPF = the catalyst pass fraction, defined as the ratio of tailpipe to engine-out emission.

The total tractive power requirements (in kW) placed on the vehicle (at the wheels) is shown in Equation 4:

$$P_{tract} = A \cdot v + B \cdot v^2 + C \cdot V^3 + M \cdot a + M \cdot g \cdot v \cdot \sin\theta$$

$$P = \frac{P_{tract}}{\eta_{tf}} + P_{acc} \qquad \text{Equation 4}$$

Where:

M = the vehicle mass with appropriate inertial correction for rotating and reciprocating parts (kg),

v = speed (m/sec),

a = acceleration (m/s^2),

g = the gravitational constant (9.81 m/s^2), and

 = 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,

The fuel rate in any driving cycle for any vehicle model could be calculated using Equation 5.

$$FR \approx \left(KNV + \frac{P}{\eta}\right)\frac{1}{44}$$ Equation 5

where,

k = the engine friction factor,
N = engine speed (revolutions per second),
V = engine displacement (liter),
$\eta \approx 0.4$ = a measure of indicated efficiency

and finally the engine-out emission module could be calculated using Equation 6.

$$ECO \approx [C_0(1 - \phi^{-1}) + a_{co}]FR$$
$$EHC \approx a_{HC}FR + \gamma_{HC}$$
$$ENO_x = a_{1NOX}(FR - FR_{NOX}) \text{ if>0 and 0 otherwise, for } \phi<1.05$$
$$ENO_x = a_{2NOX}(FR - FR_{NOX}) \text{ if>0 and 0 otherwise, for } \phi\geq1.05$$
Equation 6

Where:

C_0, a_{CO}, a_{HC}, and Υ_{HC} are calibrated constant coefficients that are slightly different from vehicle to vehicle.
a_{1NOX} and a_{2NOX} are engine-out NOX emission indexes in grams of emissions per gram of fuel use under stoichiometric and enrichment conditions, respectively, and
FR_{NOX} is fuel rate thresholds

One of the examples of using CMEM in the emissions research work is this following paper. (Xia et al. 2012) discussed the use of the Eco-Signal Operations approach technology. The ECO-approach technology means a traffic signal that broadcasts its signal phase and timing, and Geometric Intersection Description to the vehicle. An onboard system takes this information along with vehicle position and speed, and provides speed recommendations to the driver. This speed would be an emissions reducing optimal speed. Field tests were conducted using a test vehicle equipped with the optimal speed algorithm. Based on the vehicle speed trajectories during the test, vehicle fuel consumption is calculated using CMEM. During the two tested scenarios, vehicle emissions were reduced compared to the control, an uninformed driver.

3.1.4 Integration

INTEGRATION is a trip-based microscopic traffic and emissions simulation model. It is developed in its current version under the direction of Dr. Hesham Rahka at Virginia Tech. The software includes a traffic assignment tool, in which origin/destination (OD) matrices are entered along with departure time series histograms for each O-D pair. The INTEGRATION framework can model a range of on road vehicle types, and supports a total of 25 default options including passenger cars, light-duty trucks, and heavy-duty trucks. Similar to most industry standard traffic simulation software, vehicle operation is governed by proprietary car following, lane changing, and gap acceptance models (H. Rakha 2010).

INTEGRATION was designed with a strong basis in vehicle operation dynamics, and is intended to accurately represent acceleration and velocity at high temporal resolution. In addition, the model is designed to offer flexibility in estimating acceleration rates of both large and small vehicles on varying road types and conditions. This accuracy and flexibility is a necessity for microscopic power-based emissions modeling (H. Rakha 2010) .

INTGRATION allows the user to specify time series histograms for departures for each origin-destination pare in the simulation. The software generates individual vehicle departure time schedule from this information before the simulation is run. Departures can be fully random, or any combination of random and uniform. Calibration of the O-D demand is achieved using a maximum likelihood approach (H. Rakha and Ahn 2004). Pipes and Greenshields models were combined into a single regime model, based on desired speed and proximity to followed vehicle. This is referred to as Van Aerde's model after Michael Van Arde, the original developer of INTEGRATION. The model is calibrated using four parameters based on field data: free-speed, speed-at-capacity, capacity, and jam density. Position, headway, and speed are computed in 0.1 second time steps (H. Rakha and Ahn 2004).

INTEGRATION uses a separate acceleration and deceleration logic. Deceleration is computed based on the existing speed, the speed of the vehicle or object that is necessitating the deceleration, and the time available to decelerate. According to the developers, this can lead to asymptotic deceleration of a vehicle following another vehicle that is traveling at a constant speed. In any case, a vehicle will not continue to decelerate once it reaches the speed of the vehicle ahead of it (H. Rakha and

Ahn 2004). Vehicle acceleration in INTEGRATION is simulated with vehicle dynamics model, as opposed to the more common kinematic acceleration models. One of the problems identified with state of practice models is in their ability to represent the speed/acceleration relationship at low vehicle speeds. Most models allow acceleration to vary as a function of speed, with higher acceleration in general associated with lower travel speeds. However, there are a number of different ways of modeling this and is no definitive relationship between these two parameters. According to the developers of INTEGRATION, industry standard traffic models tend to overestimate acceleration at low speeds, which makes them poorly suited for emissions modeling. (Rakha and Ahn 2004; Rakha et al. 2001, 2004) INTEGRATION addresses this issue by constraining vehicle acceleration to the physical limitations of the vehicle as described below.

In the INTEGRATION model, power is computed as the minimum of 1) maximum tractive effort based on tire/road surface friction and vehicle weight and 2) Engine power, corrected for transmission efficiency and accessory power use. In addition to power, rolling resistance, aerodynamic drag, grade, and vehicle mass are all considered in acceleration computations. In addition, the model accounts for the fact that drivers do not typically use the maximum power available in their vehicles. The configuration differs somewhat for light duty and heavy-duty vehicles (LDV's and HDV's). The HDV model accounts for the loss in power at low speeds due to gear shifting. (H. Rakha et al. 2001) The LDV model is very similar, but assumes that the low speed power loss effect is negligible for passenger vehicles. (H. Rakha, Snare, and Dion 2004)Both the LDV and HDV models were calibrated using field data collected at Virginia Tech's Smart Road test facility in Blacksburg, Virginia.

For the HDV model, four heavy-duty diesel trucks of model years ranging from 1990 to 1998 were driven over the test course in the spring of 2001. Ten different load cases were tested on each vehicle. By changing the loading, the researchers hoped to incorporate the range of power to weight rations that would typically be observed in practice. This data was used to calibrate the power adjustment factor, which is a linear function relating engine power to vehicle speed. This factor is intended to capture the average power reduction due to gear shifting as a function of speed, as actual power fluctuates between the maximum value and zero as gear shifts take place (H. Rakha et al. 2001). Vehicle acceleration data was collected in the summer of 2001 using 13 test vehicles ranging from subcompact to light duty trucks. This data was used to calibrate and compare several state of practice vehicle acceleration models, including the dynamics model used in INTEGRATION. Comparisons were made for speed and acceleration vs. time and distance, as well as acceleration vs. speed. The results of the comparison strongly supported the vehicle dynamics model over the other state of practice models. This was a relatively simple validation, and did not involve any real world vehicle interaction or complex maneuvers (H. Rakha, Snare, and Dion 2004).

The emissions model incorporated into INTEGRATION is the Virginia Tech Microscopic energy and emission model (VT-Micro). While a full discussion of the model structure is outside the scope of this report, the model will be described as it relates to INTEGRATION. Based on the instantaneous speed and acceleration levels of individual vehicles, VT-Micro, predicts the instantaneous fuel consumption and emission rates of HC, CO, NOX and CO2 (Ahn 1998), (Hesham Rakha, Van Aerde, and Ahn 2000), and (Ahn 2002).

One important thing to note is that, when the performance envelope of the VT-Micro data is exceeded in the input speed and acceleration data, emissions will be computed at the boundary of the VT-Micro data. That is to say, the performance envelope of the VT-Micro data determines the maximum possible emission rates (H. Rakha, Ahn, and Trani 2004). Although INTEGRATION computes speed and acceleration in 0.1 second time steps, these values are averaged over 1 second time steps for emission calculations. According to supporting documentation, this does significantly reduce the accuracy of the emissions estimates, and is done to reduce the computational load.

Emission rates were collected using dynamometer tests and standardized drive cycles. The first study to develop non-high emitting vehicle emission rates was conducted in 1996 at the Oak Ridge National Laboratory (ORNL). Test vehicles included 5 light duty automobiles and three light duty trucks, and were selected to be representative of the sales proportion in terms of engine displacement, based on sales data from 1995 and 1996. The vehicles used in emission rate development were subjected to driving tests in order to develop practical performance limits that correlate to actual vehicle capabilities (H. Rakha and Ahn 2004). The general VT-Micro equations used to calculate the instantaneous fuel consumption and emission rates of individual vehicles could be seen in Equation 7**.**

$$MOE_e = \sum_{i=0}^{3}\sum_{j=0}^{3} exp\left(k_{i,j}^{e} * v_{VT}^{i} * a^{j}\right), for\ a \geq 0$$
$$MOE_e = \sum_{i=0}^{3}\sum_{j=0}^{3} exp\left(l_{i,j}^{e} * v_{VT}^{i} * a^{j}\right), for\ a < 0$$

Equation 7

Where:

MOE_e = Instantaneous fuel consumption or emission rate (L/s or mg/s),

a = Instantaneous acceleration of vehicle (km/h/s),

v = Instantaneous speed of vehicle (km/h),

$k_{i,j}^{e}$ = Vehicle-specific acceleration regression coefficients for MOEe, and

$l_{i,j}^{e}$ = Vehicle-specific deceleration regression coefficients for MOEe.

Since the initial release, the VT-Micro model has been updated to include emissions data from 87 additional cars and trucks. This update is described in documentation related specifically to VT-Micro, but it is stated that the updated model has been included in the current release of INTEGRATION. (H. Rakha and Ahn 2004)This data were gathered by the EPA using dynamometer tests at the Automotive Testing Laboratories, Inc., in Ohio and EPA's National Vehicle and Fuels Emission Laboratory (NVREL), in Ann Arbor, Michigan in the spring of 1997. Vehicles of model years 1986 to 1996 were drafted at random from inspection and maintenance lanes in Ohio. Vehicles were screened to separate high emitting from non-high emitting vehicles, and separate rates developed for each group. In the screening process, 60 vehicles were identified as non-high emitters and 37 as high emitters. Each vehicle was tested on 14 to 16 different drive cycles to insure that the full range of acceleration/speed combinations was captured. In addition to the typical vehicle categories of light duty and heavy duty, statistical methods were used to define 5 LDV and 2 light duty truck (LDT) categories.

Emission rates were developed from test data using the methods described in VT-micro model supporting documentation. (H. Rakha, Ahn, and Trani 2004) Regression equations were developed to represent emission rates as functions of speed, power, and acceleration. Separate regression equations were developed for positive and negative acceleration, because engine power is exerted in positive acceleration while none is exerted in negative acceleration. An optimal temporal shift of approximately 6 – 8 seconds was computed to deal with the time lag between acceleration and tail pipe emissions.

Aggregate and instantaneous emission rates were validated using a number of drive cycles, but no validation was performed (at least in the rate development studies) using microsimulation vs. real world data. The documentation of the rate development studies is focused primarily on the emission vs. acceleration and speed relation, as opposed to the simulated vs. real world relationship.

3.1.5 PARAMICS

Paramics is a microscopic traffic simulation software package published by Quadstone in Edinburgh Scotland. Interestingly, there are actually two similar microscopic traffic simulation software titles published under the name Paramics, the Quadstone product and “S-Paramics” which is published by SIAS in Edinburgh. According to the SIAS company website, the similarity in both name and underlying model is the result of a partnership between Quadstone and SIAS that was dissolved in 1998 (SAIS 2012). Here the focus is on the Quadstone product for several reasons. One, Quadstone Paramics has more functionality in terms of emissions modeling. S-Paramics does have a built in emissions model, but it is out of date and has limited functionality. In addition, Quadstone Paramics contains “Paramics API”, which is a tool for creating and utilizing added functionality, such as integrating Paramics with external emissions models (Quadstone 2012).

Paramics allows a good deal of user flexibility in terms of vehicle behavior, signal timing, and data collection (Speirs and Braidwood 2004). Paramics is advertised as “fully scalable”, which means that a broad range of network scales can be modeled, from a single intersection to an entire city(Quadstone 2012). Simulated vehicles are represented as “Driver-Vehicle units” (DVU’s), each of which is assigned a number of physical and decision characteristics including vehicle geometry and performance parameters, familiarity with the traffic network, aggressiveness and origin-destination information. DVU route selection can be made in three different ways, including deterministic, stochastic cost weighting, and dynamic feedback which is a real-time decision structure based on driver familiarity and traffic conditions. The “Advanced” version of the software also contains an OD estimating tool (Quadstone UGM 2009). Vehicle movement across a network is determined by Quadstone’s proprietary car-following and lane-change models (Quadstone Paramics V5.0 Technical Notes 2004). For signal timing, Paramics has the ability to model fully actuated and demand responsive signal plans, with the option to change signal parameters as the model is running. This allows the user to make changes to signal timing and immediately observe the effect on traffic flow. Paramics apparently does not include an automatic traffic signal optimization application, but does include a number of up to date tools designed to aid the user in visualizing and optimizing signal timing and other traffic control mechanisms (Quadstone 2012).

One notable component of Quadstone Paramicss is Monitor, a proprietary emission modeling tool. However, little documentation was found that describes either the methodology or underlying data used in this application. Based on the limited documentation available, it is clear that Monitor utilizes tables that contain vehicle exhaust emissions and fuel consumption rates as a function of vehicle type, speed, and acceleration (M. Barth, Younglove, and Scora 2005). The software simply looks up values for each second in the analysis to compute pollutant quantities and fuel consumption. It is likely that, in most cases, emission rates will be provided by the user because of the inadequacy of emission data contained in Monitor. In one study, emission rates were computed for each second in the analysis using a CMEM plug-in developed in the Paramics API, which demonstrates the flexibility that the API tool provides (M. Barth, Younglove, and Scora 2005).

Another example for using PARAMICS in the emissions related research work is this following paper. (Boriboonsomsin and Barth 2008) studied the impact of freeway high-occupancy vehicle lane configuration, continuous access HOV and limited access HOV, of vehicle emissions. In this paper authors used an emissions modeling methodology that integrates PARAMICS, a microscopic traffic simulation model, with CMEM, a modal emissions model to estimate vehicle emissions from these two types of HOV lane configurations. As a conclusion for this paper, it was found that the emissions in freeways with continuous access HOV lane are consistently lower than emissions from freeways with limited access HOV lane. This result was justified by mentioning that the dedicated ingress/egress sections on the freeway with limited access HOV lane are having highly concentrated weaving maneuvers that take place on, which cause acceleration/deceleration events to occur with higher frequency and magnitude.

3.2 Mesoscopic Models

Mesoscopic models combine the properties of microscopic and macroscopic simulation models. They generally represent most entities at a high level of detail but describe their activities and interactions at a much lower level of detail than would a microscopic model provides. Generally, they provide more coverage with less modeling detail than microscopic simulation. Similar to microscopic models, the mesoscopic models' unit of traffic flow is the individual vehicle. However, the movement of these vehicles in mesoscopic models follows the approach of the macroscopic models and is governed by the average speed on the travel link (Lieberman and Rathi 1997), (Dowling, Holland, and Huang 2002), and (Alexiadis, Jeannotte,, and Chandra 2004).

3.2.1 The MEASURE Model

Researchers at The Georgia Institute of Technology developed the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE). MEASURE is basically a GIS-based emissions model. It can calculate estimates of HC, CO, and NOx. Two major modules are included in MEASURE. The first one is the start emissions module, while the second one is the on-road emission module (Bachman et al. 2000). Refined tree-based regression analysis of vehicle emission test data were used to calculate the emission rates in MEASURE. In MEASURE, emission rates are a function of pollutant, vehicle model year, vehicle fuel delivery technology, high or normal emitter vehicle, and modal variables. Source of data is from EPA and California Air Resource Board.

Vehicle emissions for the On-Road emission module are estimated based on different operating modes. These modes are: idle, cruise, acceleration, and deceleration. Average travel speed, roadway characteristics, traffic flow, and volume to capacity ratio are used to build the vehicle operating modes. Vehicle registration data was used to get vehicle cold and hot-start characteristics distribution, and then estimate the start emission module. The start emission estimates will be based on start characteristics distribution and start emission rates (Bachman et al. 2000).

3.2.2. DYNASMART-P:

DYNASMART (DYnamic Network Assignment-Simulation Model for Advanced Road Telematics) is currently supported by the Federal Highway Administration through McTrans. DYNASMART-P provides lots of features like: the capability of modeling big networks, importing of network and demand data from other planning models, enhanced loading and display speed for large-scale network datasets, and emissions models for light-duty vehicles (Mehta et al. 2003).

The used emission models in DYNASMART-P are adapted from the look-up tables for fuel consumption and emissions developed at Oak Ridge National Laboratory (ORNL) in the mid-1990s (ORNL models). These fuel consumption and emissions models are based on functions of vehicle speed and acceleration. DYNASMART-P is using ONROAD models developed at Texas Southern University for heavy-duty vehicles. EPA also accepted MOBILE 5 to be also interfaced with DYNASMART-P for additional analysis. More details for the developed methodology of these used models, the look-up tables, and their evaluation with other emission models like INTEGRATION could be found in these following resources: (H. Rakha et al. 2000), (West et al. 1997), and (U.S. Department of Transportation, Washington D.C., FHWA 1999).

3.3 Macroscopic Models

Macroscopic simulation models are designed for operations analyses of systems of road facilities. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. Macroscopic models are based on the deterministic relationships of the flow, speed, and density of the traffic stream. In these models, entities and their activities and interactions are described at a low level of detail, while minor details,like the lane change maneuvers, would not be presented at all (Lieberman and Rathi 1997), (Dowling, Holland, and Huang 2002), and (Alexiadis, Jeannotte,, and Chandra 2004).

3.3.1 MOVES (Motor Vehicle Emission Simulator)

The most recent release, MOVES2010b, is the EPA's newest multi-scale on-road emissions model. It has replaced MOBILE 6 as the preferred software for State Implementation Plans and Transportation Conformity Analyses. Although it is considered by the EPA to capable of modeling at macro, meso, and micro scale, it is not a traffic simulator and vehicle activity data must be input by the user for smaller scale modeling. In macro scale computes vehicle activity is based on nationwide "vehicle miles traveled" data, which is not precise enough for mesoscopic and microscopic scale analysis (EPA 2012). That said, MOVES contains an impressive amount of emissions and vehicle data, and can be used with a microscopic traffic simulator to model system-level changes. Emissions data for light duty passenger vehicles is based largely on inspection maintenance test data from the Phoenix Arizona area. This data dates from 1995 to 2005, and was collected from approximately 62,500 vehicles (EPA 2011a). Heavy-duty and additional light duty vehicle and emissions data is based on a number of different studies, all using American vehicles and driving conditions. In general, the EPA loosely based data requirements for each vehicle subgroup on the population of that vehicle type currently on the road. As a result, some emission rates (such as those for heavy duty gasoline vehicles) are based on a comparatively small quantity and range of actual data (EPA 2011b). Some emission rates were determined using on road vehicle operation, others were simply calculated from dynamometer tests using EPA standard drive schedules.

Over 60 different pollutants can be modeled separately in MOVES, which likely the most on any emission model currently available. Basic emission rates in MOVES such as Fuel consumption, NOx, and CO are a function of vehicle specific power (VSP), and are in units of mass/time (EPA 2011a). Many minor pollutants and all air toxics are computed as fractions of major pollutant quantities. The software corrects for a number of scenario variables, including meteorological conditions, startup emissions, and local inspection and maintenance program effects. Simulation is conducted in 1-second time steps and generates output in the form of MySQL database tables.

At the micro scale, there are two preferred ways to input vehicle activity information. One, activity is input separately for each link in the modeling area is input in the form of a second-to-second vehicle velocity profile. This can come from actual vehicle travel logs, EPA standard drive cycles, or from microscopic simulation output. This is used along with default vehicle characteristics to generate a time distribution of vehicle operating modes differentiated according to the MOVES classification system by VSP. Alternatively, the user can provide the operating mode distribution directly as an input table. Total activity is computed in units of time based on average speed and link geometry, and this is used with the operating mode distribution to compute the time spent in each emission rate-specific operating mode (EPA 2011a).

MOVES was used in many researches in the last ten years. Here is one example of these researches. (Hallmark and Mudgal 2012) reviewed a study conducted to compare the vehicle activity of a roundabout to other intersections. It is suggested that roundabouts are more efficient and this study is to test this hypothesis. The study was completed on-road instrumentation to record second by second vehicle activity, i.e. instantaneous speed and acceleration. This vehicle activity data were inputted into MOVES and mathematical equations for the vehicle specific power (VSP) bins are used to estimate the emissions for the three different traffic controls. The VSP bins separate emissions rates and data is placed into bins based on the emissions rate recorded. With these bins you can see where the majority of the data points lie. The data shows that roundabouts have higher vehicle emissions through the intersection however they are not in the "system" as long. This means more experimentation needs to be completed for vehicle emissions over a time period.

Another example for using MOVES is this following paper. (Qiao et al. 2012) looked at the concept that if vehicles can communicate with stop signs drivers so can start to slow earlier without physically seeing the stop sign. Preemptively locating stop signs can result in more fuel efficient stopping. In order to communicate to the vehicles the authors analyzed the use of Radio Frequency Identification (RFID) devices. RFIDs have already been implemented in the transportation discipline. MOVES was used alongside incorporated VSP bin distributions and their related emissions rates. Average emissions were found from the MOVES binning and PEMS emissions data. Emissions rates were estimated for vehicles with and without the RFID. The vehicle with the RFID had lower emission rates no matter which direction the driver chose to go once leaving the intersection.

3.3.2 Watson Model

A fuel consumption model was developed by Watson et al. using average speed data. the changes in the positive kinetic energy during acceleration was used as a predictor variable in this model, But the effects of speed changes during the deceleration phase are not included. (Watson, Milkins, and Marshall 1979). It is worth to say also that the effect of aerodynamic drag on fuel consumption becomes significant at higher average speeds (at average speeds over 55 km/h), and this is also is not included in the study (EVANS and HERMAN 1978).The fuel consumption-space mean speed relationship could be seen in Equation 8:

$$F = K_1 + \frac{K_2}{V_s} + K_3 V_s + K_4 PKE$$
$$PKE = \sum (V_f^2 - V_i^2)/(12.960 X_s)$$

Equation 8

Where,

F = fuel consumed (L/km)

V_s = space mean speed (km/hr)

PKE represents the sum of the positive kinetic energy changes during acceleration in m/s^2,

V_f = final speed (km/hr) f

V_i = initial speed (km/hr) i

X_s = total section length (km)

SUMMARY AND CONCLUSION

The main goal of this paper is to synthesize and document the different aspects of emissions inventories, models, and optimization of these models. The synthesis work presented in this paper focused on three main areas: fuel consumption and emission modeling tools for signalized intersection operation, sources of emissions inventory and data used in the models, and finally how to optimize these emission models. In the first part of this paper, the authors started in giving some details about the definition, importance, and methods of calculation of emission inventories, emission factors, and some of the currently available emission inventories. After that and in the second part, the authors reviewed currently available fuel consumption and emission models suitable for modeling traffic operations at signalized intersection approaches. The review in this second part included three different analysis levels: microscopic models, mesoscopic models, and macroscopic models. In the third part of this paper, the authors provided documentation for the optimization of fuel consumption and vehicle emission models. The organization of this section consisted of techniques that utilize mathematical models, simulation packages, and in-the-field systems. All of these topics are supposed to form a good base for those who are interested to take a comprehensive introduction for the research work done in the fuel consumption and emissions fields.

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