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Heavy-Duty Diesel Vehicle Modal Emission Model (HDDV-MEM) Volume II: Model Components and Outputs

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Heavy-Duty Diesel Vehicle Modal Emission Model (HDDV-MEM) Volume II: Model Components and Outputs

by

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Abstract

The research reported in this document outlines a proposed heavy-duty Diesel vehicle modal emission modeling framework (HDDV-MEMF) for heavy-duty diesel-powered trucks and buses. The heavy-duty vehicle modal modules being developed under this research effort, although different from the structure within the motor vehicle emissions simulator (MOVES) model, should be compatible with it. In the proposed HDDV-MEMF, emissions from heavy-duty vehicles are predicted as a function of hours of on-road operation at specific engine horsepower loads. Hence, the basic algorithms and matrix calculations in the new heavy-duty diesel vehicle modeling framework should be transferable to MOVES. The specific implementation approach employed by the research team to test the model in Atlanta is somewhat different from other approaches in that an existing geographic information system (GIS) based modeling tool is being adapted to the task. The new model implementation is similar in general structure to the previous modal emission rate model known as the Mobile Assessment System for Urban and Regional Evaluation (MEASURE) model.

Sponsored by the U.S. Environmental Protection Agency, this exploratory framework is designed to be applied to a variety of policy assessments. The model can be used to evaluate policies aimed at reducing the emission rates from heavy-duty vehicles as well as policies designed to change the on-road operating characteristics to reduce emissions.

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Sally Gutierrez, Director
National Risk Management Research Laboratory

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Acronyms

AADT	annual average daily traffic
ahp	axle horsepower
bhp	brake-horsepower
bhp-hr	brake-horsepower hour
CARB	California Air Resources Board
CO	carbon monoxide
CPC	Climate Prediction Center
DOT	Department of Transportation
EMFAC2002	California's mobile source emissions model
FHWA	Federal Highway Administration
g/mi	grams per mile
g/s	grams per second
GDOT	Georgia Department of Transportation
GIS	geographic information system
HDDV-MEM	Heavy-Duty Diesel Vehicle Modal Emission Model
HDDVs	heavy-duty diesel vehicles
HDV	heavy-duty vehicle
HPMS	Highway Performance Monitoring System
MOBILE6	EPA's mobile source emission factor model
MOVES	motor vehicle emission simulator
mph	miles per hour
mph/s	miles per hour per second
NO_X	oxides of nitrogen
PM	particulate matter
U.S. EPA	U.S. Environmental Protection Agency
UDDS	urban dynamometer driving schedule
VMT	vehicle miles traveled
VOC	volatile organic compounds
ZML	zero-mile level

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Overview

A Georgia Institute of Technology (Georgia Tech) research team in the School of Civil and Environmental Engineering has recently completed development of a new heavy-duty diesel vehicle (HDDV) modal emission modeling framework (Guensler et al., 2005). The HDDV modal emission model (HDDV-MEM) first predicts second-by-second engine power demand as a function of on-road vehicle operating conditions and then applies brake-specific emission rates to these activity predictions (Yoon et al., 2005a). On-road operating modes (cruise, acceleration, deceleration, and motoring/idling) are integral in the power demand functions, as are other relevant factors such as vehicle weight, road grade, road surface type, and so forth (Feng et al., 2005).

The HDDV modal emissions model (HDDV-MEM) consists of three modules: a vehicle activity module (with vehicle activity tracked by vehicle technology group), an engine power module, and an emission rate module. Each module performs a series of routines designed to estimate on-road vehicle activity and operating conditions for each vehicle technology group, estimates engine horsepower demand for each technology group and roadway link, and then calculates resulting emissions from these on-road activities. The three modules are initiated with modeling parameters defined in model input command lines. Once modeling parameters are defined in the command window, each module processes in parallel and serial to predict HDDV emissions on each roadway link (Figure 1).

In the vehicle activity module, on-road HDDV volumes in vehicles-hours per hour (veh-h/h) are estimated using total vehicle volumes obtained from the highway performance monitoring system (HPMS) daily volumes, vehicle-miles-traveled (VMT) fractions for each vehicle class, diesel fractions, and hourly vehicle volume profiles.

In the engine power module, the engine horsepower demand (brake-horsepower) for each roadway link is calculated for each technology group. Power demand is predicted by applying speed-acceleration matrices, vehicle weight distributions, auxiliary power requirement estimates, environmental conditions, roadway link characteristics, and a variety of applicable parameters associated with vehicle physical characteristics. Power demand includes tractive power demand plus auxiliary power demand associated with running refrigeration units and other equipment onboard the heavy-duty vehicles. On-road activity with positive tractive power demand (and all activity with auxiliary power demand) is linked directly to work-related emission rates (grams per brake-horsepower-hour per vehicle). Activity for which tractive power demand is less than or equal to zero, which a vehicle is under the motoring mode, is linked to idle emission rates (grams per hour per vehicle).

The emission rate module provides work-related emission rates (grams per brake-horsepower-hour per vehicle) and idle emission rates (grams per hour per vehicle) for each technology group. Work-related emission rates are derived from EPA's baseline running emission rate data, and idle emission rates are derived from the California mobile source emissions model EMFAC2002 idling emission rate test data. Diesel vehicle registration fractions and annual

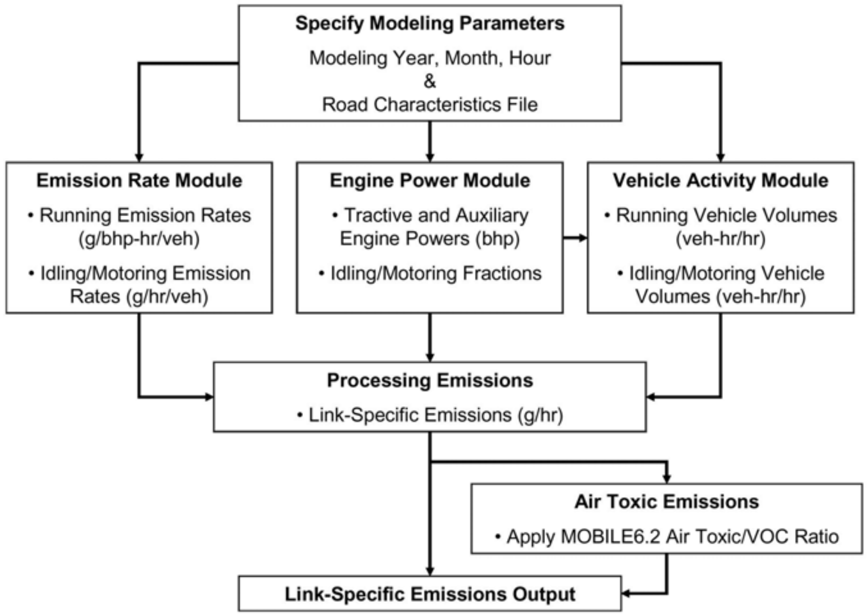

Figure 1. Heavy-Duty Diesel Vehicle Modal Emission Modeling Process.

mileage accumulation rates are employed to develop calendar year emission rates for each technology group.

Vehicle volume estimates, engine horsepower demand, and calendar year (modeling year) emission rates are joined to calculate total mass emissions in grams per hour (g/h) for volatile organic compounds (VOC), carbon monoxide (CO), oxides of nitrogen (NO_X), and particulate matter (PM) for each vehicle type on each roadway link. Toxic air contaminant emissions rates (benzene, 1,3-butadiene, formaldehyde, acetaldehyde, and acrolein) are also estimated in grams per hour for each vehicle type using the MOBILE6.2-modeled ratios of air toxics to VOC for each calendar year.

HDDV-MEM output files provide not only hourly emissions, but also aggregated total daily emissions (in accordance with input command options). The structure of the output files are such that hourly emissions predictions can be directly incorporated with roadway network features in geographic information systems (GIS) environment for use in interactive air quality analysis (regional and microscale).

Vehicle Technology Groups

To properly link baseline diesel emission rates with on-road vehicle class, the research team has developed a new vehicle technology grouping methodology, which associates EPA engine size classes, EPA heavy duty vehicle (HDV) classes, Federal Highway Administration (FHWA) truck classes, and field observation X classes (Yoon et al., 2004). Three engine classes (light, medium, and heavy) were allocated into each EPA HDV class. To translate FHWA truck classes into EPA HDV classes, X classes were modified to cross-link between both the EPA HDV and FHWA truck classes. The X1 class was separated to X1A and X1B classes for light and medium engines because baseline emission rates were significantly different across these engine classes. The X2 class was separated into X2A and X2B classes for 3-axle single unit and double unit trucks. This was because 3-axle double unit trucks travel more than 2.5 times further than 3-axle single unit trucks (Yoon, 2005b). X3 class was also separated to X3A and X3B classes for 4-axle FHWA truck and greater than 4-axle FHWA truck classes, because engine horsepower ranges were statistically different across these two classes (Figure 2, Ahanotu, 1999). School and urban buses were assigned to X4 and X5 classes, respectively.

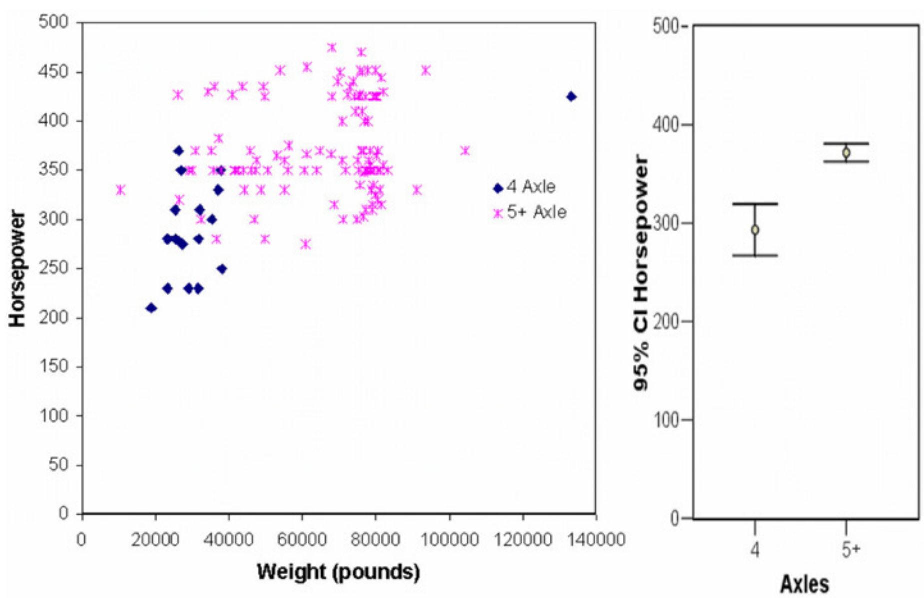

Figure 2. Horsepower Distributions for 4-axle and 5+axle Vehicles.

With the creation of sub-groups and additional groups from the original X-scheme, a new vehicle technology grouping map was created (Table 1). Using this map, vehicle classes can be translated from FHWA truck classes to EPA HDV classes and vice versa.

The technology group classes employed in the current version of the model are statistically based and can be modified as warranted when supplemental analyses of emission rate data and field observations indicate that such modifications would serve to further refine the model. There is no practical limit to the number of technology groups that can be employed in the model. Each technology group simply needs to be coded for tracking in the vehicle activity and emission rate modules. Addition of technology groups does add more complexity and model computation time, so the basic goal is to ensure that further refinement of technology groups provides improvements in model accuracy without significantly sacrificing model efficiency. This is one of the basic goals of the ongoing data analysis being undertaken by the model development team in the phase II study, 2005.

Table 1. Vehicle Technology Grouping Map.

X Class	EPA Class			FHWA Class
	Engine Size	HP Range	HDV Class	
X1A	Light	70–170	HDDV2b	3 (HDV)
			HDDV3	5
			HDDV4	
			HDDV5	
X1B	Medium	170–250	HDDV6	
			HDDV7	
X2A	Heavy	>250	HDDV8a	6
X2B			HDDV8a	8 (3 axle)
X3A			HDDV8b	7, 8 (4 axle)
X3B			HDDV8b	9 to 13
X4			SCHBUS	4
X5			URBUS	4

Vehicle Activity Module

The vehicle activity module provides hourly vehicle volumes for each vehicle technology group on each transportation link in the modeled transportation system (Equation 1). The annual average daily traffic (AADT) estimate for each system link (coded by road and adjusted to link direction) is processed to yield vehicle-hours of operation per hour for each technology group (using truck percentages, VMT fraction by vehicle technology group, diesel fraction, hourly volume apportionment of daily travel, link length, and average vehicle speed).

$$VA_{v,h,s|f} = AADT_s \times \left(NL_s / TNL\right) \times HVF_{v,h} \times VF_V \times DF_v \times \left(SL_s / AS_v\right) \quad (1)$$

where VA is the estimated vehicle activity in vehicle hour per hour,
v is the vehicle technology group,
h is the hour of day,
s is the transportation link,
f is the road type for the link,
$AADT$ is the annual average daily traffic for the link,
NL is the number of lanes in the specific link direction,
TNL is the total number of lanes on the link,
HVF is the hourly vehicle fraction,
VF is the VMT fraction for each vehicle technology group,
DF is the diesel vehicle fraction for each technology group,
SL is the link length (miles), and
AS is the link average speed of the technology group in miles per hour.

To estimate on-road running emissions from each link, two sets of calculations are performed. On-road vehicle activity (vehicle-hour) for each hour is multiplied by engine power demand for observed link operations (positive tractive power demand plus auxiliary power demand), and then by baseline emission rates (grams per brake-horsepower-hour per vehicle). As discussed in the engine power module section, these calculations are processed separately for each speed/acceleration matrix cell. Emissions from motoring activity are calculated by first determining the vehicle-hours of motoring activity on each link for each hour (Equation 2) and multiplying by the baseline idle emission rate (grams per hour per vehicle). The fraction of motoring activity is calculated in the engine power module. Figure 3 outlines the modeling procedure.

$$MVA_{v,h,s|f} = VA_{v,h,s|f} \times MF_{v,h} \quad (2)$$

where MVA is the motoring vehicle activity in vehicle hour per hour, and
MF is the motoring activity fraction determined in the power demand module.

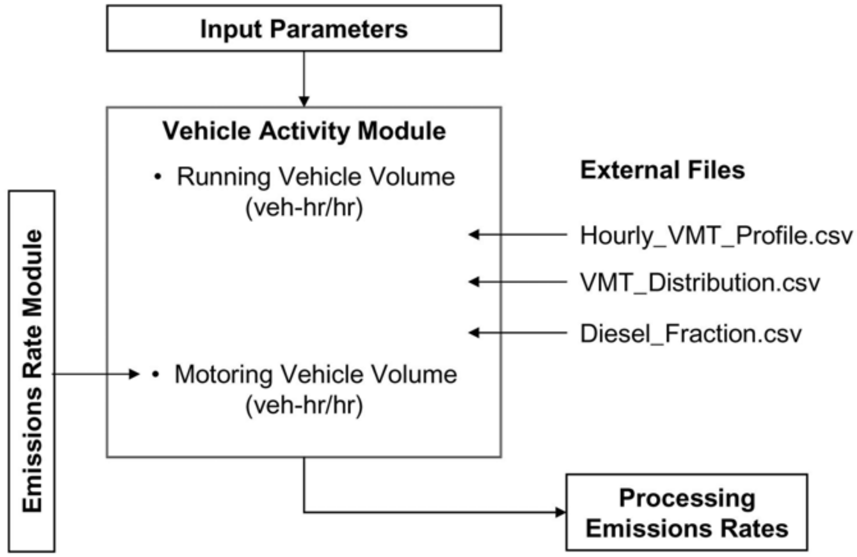

Figure 3. Vehicle Activity Module Process.

Engine Power Module

In the engine power module, engine power demand to overcome external forces (rolling resistance, aerodynamic drag, and so forth) and to move a vehicle forward can be estimated for each vehicle class and for each vehicle year. Engine power demand consists of two terms: instantaneous tractive power demand and continuous auxiliary power demand. Instantaneous tractive power demand is calculated with acceleration force, rolling resistance, gravitational force, aerodynamic drag, and rotational inertial loss. Continuous auxiliary power demand is tabulated from duty-cycle-based average heavy HDV auxiliary power requirements obtained from the 2004 Automotive Handbook (SAE, 2004), by season (summer and winter), and by time of day (day and night). Equation 3 expresses the estimation of overall required engine power (unit conversions omitted).

$$P_{v,h,f,s} = \sum_i \sum_j \left[\left(V \times AFF \times \left(\left(\frac{W}{g} \times a \right) + F_R + F_W + F_D + F_I \right) \right)_{i,j|v,h,f,s} + AP_{i,j|v,h} \right] \tag{3}$$

where P is the engine power demand in brake-horsepower,
i is the speed bin from the applicable speed/acceleration matrix,
j is the acceleration bin from the applicable speed/acceleration matrix,
V is the vehicle speed for each speed/acceleration bin in miles per hour,
AFF is the acceleration frequency fraction for each speed/acceleration bin,
W is the actual vehicle weight in pounds force,
g is the gravitational acceleration (32.2 ft/s^2),
a is the vehicle acceleration in feet per second squared,
F_R is the rolling resistance in pounds force,
F_W is the gravitational force in pounds force,
F_D is the aerodynamic drag in pounds force,
F_I is the drive train rotational inertial loss in pounds force, and
AP is the auxiliary power demand in brake-horsepower.

To integrate Equation 3 into the model, a series of tables was generated for the various parameters (roadway characteristics, speed/acceleration matrices, vehicle weight profiles, auxiliary power, vehicle characteristics, and environmental conditions). Figure 4 illustrates the general calculation process and identifies the external data sources required for estimation of engine horsepower demand for each vehicle class on a specific roadway link.

The deceleration rate of a vehicle depends upon the drivers' driving habits and roadway geometry (intersections and road grades). In the absence of proven models to predict driver behavior, the factors causing positive and negative vehicle acceleration cannot be readily identified (i.e., it is not easy to determine whether deceleration events are the result of road grade, driver response to external traffic conditions, or natural driving variability). However, observed speed/acceleration profiles can be employed to represent the combined effects noted under certain roadway operating conditions such as vehicle class, time of day, congestion level, and so forth.

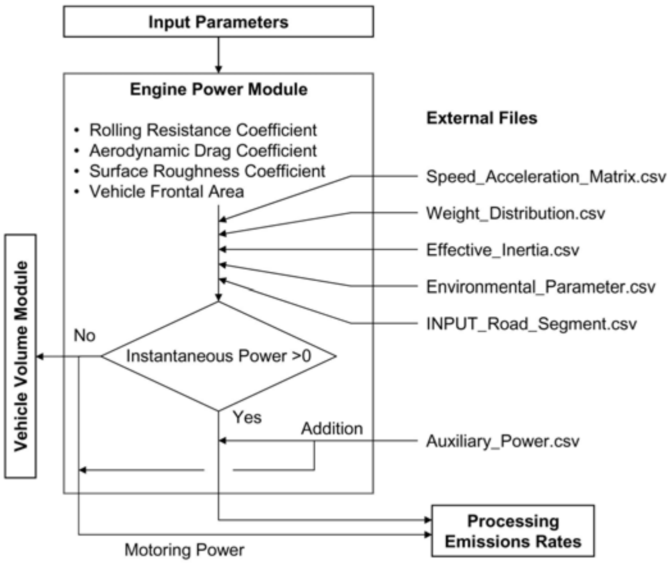

Figure 4. Engine Power Module Process.

Using Equation 3, the tractive power demand and auxiliary power demand are summed to obtain the instantaneous engine power demand for activity represented in each speed/acceleration matrix cell. Note, however, that negative or zero tractive power demand can result while a vehicle is decelerating and will result when the vehicle is idling.

Because separate emission rates are not currently available for motoring activity, the model currently operates under the assumption that motoring emission rates are not significantly different from emissions under idle conditions (this ignores any potential fuel control issues for motoring). If the tractive power demand in a matrix cell is greater than zero, the auxiliary power demand is added to the tractive power demand, and then the combined engine power demand in the cell is weighted by the speed/acceleration activity frequency in the cell to provide the weighted contribution to power emissions. If the instantaneous engine power demand is less than or equal to zero, the vehicle activity is defined as motoring activity, and only the auxiliary power demand is weighted by the activity frequency in the cell. Hence, if the tractive power demand in a cell is less than zero, the power demand for the activity in the cell is set to the auxiliary power demand. For motoring activity fractions, the idle emission rate is also applied, so that the net hourly emissions associated with motoring activity is the sum of the auxiliary power demand emissions and idle emissions.

Roadway Characteristics

The roadway characteristics table contains selected infrastructure parameters that were obtained from Georgia Department of Transportation (GDOT) HPMS database (GDOT, 2004a). These parameters are required for power demand estimation and for use in GIS analysis. Table 2 summarizes the roadway data elements. A critical roadway parameter is the assigned speed/acceleration matrix, which establishes the cumulative distribution function of vehicle speed

Table 2. Parameters in the Roadway Characteristics Table.

From GDOT HPMS	Through GIS Spatial Analysis	From Speed/Acceleration Matrices
• County code • RcLink ID[a] • Mile (link) point • Speed limit • Number of left lanes • Number of right lanes • Surface material type • Road type • Annual average daily traffic (AADT) • Truck percent	• Link start and end *X*- and *Y*-coordinates • Link length (miles) • Left and right lane slopes	• percent of vehicle activity by speed/acceleration bin • Average speed

[a] RcLink = record link, a unique record number.

and acceleration in a binned format. Speed/acceleration matrices can be assigned to specific vehicle technology groups, operating on a specific roadway link, by time of day if such data resolution is available. Alternatively, aggregate speed acceleration profiles can be assigned to groups of technology groups, groups of hours, and roadway classifications.

GDOT HPMS

- For roadway links, the number of lanes in each direction (left and right) is identified for use in estimating vehicle volume in each direction, to differentiate between inbound and outbound facility volumes. Vehicle volumes in different directions also differ by time of day (this requires local information outside of the HPMS data). Unless specific directional volumes are available, the total HPMS vehicle volume is separated directionally using the directional lane ratio.
- The surface material codes, classified by four surface material types, address typical road surface material coefficients in the calculation of rolling resistance. The four surface material types are good-smooth concrete, worn concrete or good asphalt, brick, and worn asphalt with codes of "I", "J", "K", and blank, respectively. Road surface material coefficients of 1.0, 1.2, 1.2, and 1.5 are assigned for surface material codes of "I", "J", "K", and blank, respectively (Gillespie, 1992).
- FHWA road functional classes, as well as EPA road functional classes (freeway, arterial, local, and ramp) are created based on the FHWA road functional classes and speed limits (Guensler et al., 2004). These FHWA and EPA road functional classes provide the bridge to applicable model parameter tables.
- AADT is used to estimate HDDV volumes for each EPA HDDV vehicle class or for each X vehicle class.
- By definition, truck percent from the HPMS includes only the FHWA truck classes 5 to 13, and does not include 2-axle, 4-tire heavy-duty vehicles such as the EPA HDDV class 2b. Therefore, AADT weighted by truck percent are only apportioned into EPA HDDV classes 3 to 8b and buses. HDDV2b VMT was estimated by AADT and HDDV2b VMT fractions estimated from 1993 to 1999 Highway Statistics Series.

Road Grade via GIS Spatial Analysis

To estimate the roadway slopes for each link on the HPMS road network, 2-dimensional and 3-dimensional distances were calculated through the GIS spatial and 3-dimensional analyst tools. Because the HPMS road network does not have elevation information, the 2-dimensional roadway network was converted to the 3-dimensional roadway network through the interpolation process with Georgia State Digital Elevation Model in 1:24,000-scale, downloaded from GDOT GIS Clearinghouse (GDOT, 2004b). After the interpolation process, 2-dimensional and 3-dimensional distances between a from-node and a to-node were calculated for each link. Then, link slopes in degrees were calculated with distances. Because a roadway link is represented with a single line without considering directions (left or right lanes), slopes calculated for one direction (right lanes) were used for left lane slopes with addition of a negative sign. To avoid GIS slope calculation errors, slopes greater than +5.4° (+12%) or -5.4° (-5.4%) were suppressed to +5.4° or -5.4°. Cut and fill sections are present in the network, especially for freeway links. Hence, the current slope estimation approach will overestimate the contribution of grade to regional emissions. The freeway slopes will be updated with field-measured values in the next model iteration.

Average Speed

The average speed for each link is used to estimate total vehicle-hours of travel on a link for each hour, given the predicted traffic volumes. The average speed for each roadway link can be taken directly from the speed/acceleration matrix applied to each link. The median speed of each speed/acceleration matrix cell is weighted by the activity frequency in the call and summed across the speed/acceleration matrix. In the current application of the model in Atlanta, HDDV on-road operating data are not sufficient to develop link-specific speed/acceleration matrices. In the current model application, the research team has applied road-type speed/acceleration matrices. Because the average speeds would be the same on every freeway link regardless of posted speed limit (because they would be calculated using the same matrix), the calculated average speeds for use in the model are shifted up or down as a function of the posted speed limit. The research team acknowledges that the modeling method is very sensitive to the speed/acceleration operating profiles and that the current approach in the Atlanta application does not provide a realistic representation of speed/acceleration matrices across roads (nor a realistic estimate of the average speed). However, these matrices and average speeds will be employed in Atlanta until road-specific and link-specific matrices are developed.

Speed/Acceleration Matrices

In the current version of the model, the team has focused on the model structure and implementation. The model employs speed/acceleration matrices in the estimation of tractive engine power demand (Yoon et al., 2005c). Speed and acceleration both contribute to tractive load and therefore engine load, as outlined in Equation 3. Only two speed/acceleration matrices have been integrated into the beta test version of the model. One matrix was created with data obtained from Grant's speed and acceleration data (Grant, 1998) and the other represents the EPA Urban Dynamometer Driving Schedule (UDDS) for heavy-duty vehicles (U.S. EPA, 2004). Because Grant's speed and acceleration data were obtained from freeways, the data were used to develop a freeway speed/acceleration matrix. For the other roadways (arterials, locals, and ramps), the speed/acceleration matrix developed from UDDS was used. Figure 5 and 6 show speed-acceleration frequency profiles for freeways and the other roadways.

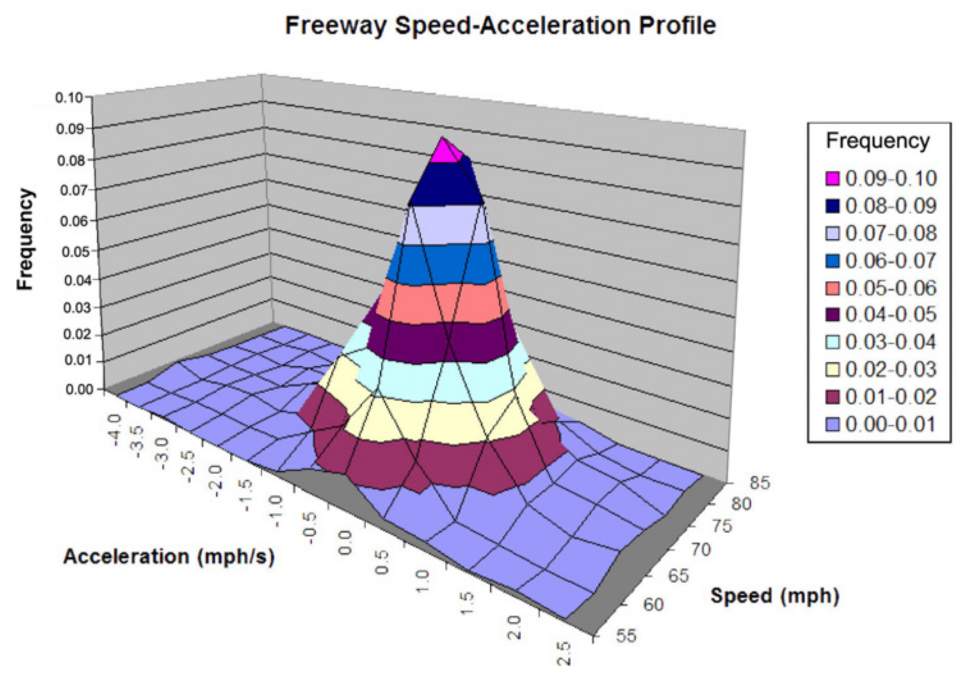

Figure 5. Freeway HDV Speed-Acceleration Profile (Grant, 1998).

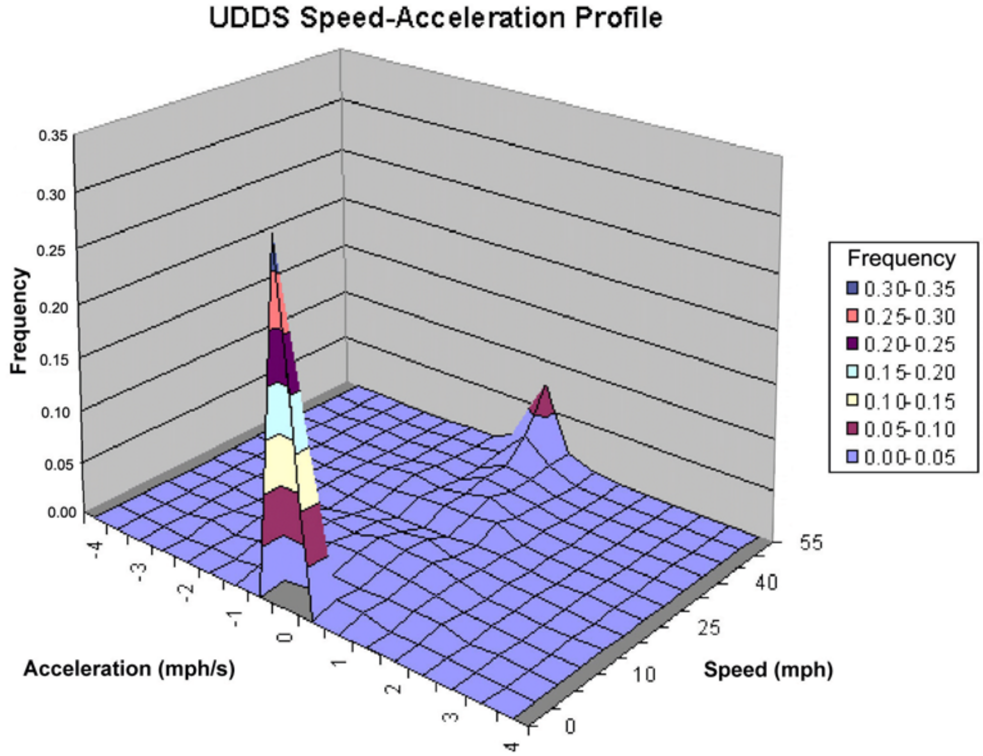

Figure 6. UDDS Speed/Acceleration Profile from UDDS.

Vehicle Weight Profiles

For the vehicle weight profiles, the research team used actual vehicle weights measured nationwide in 1999 and 2000 (Lindhjem et al., 2004). From measured vehicle weights, hourly vehicle weight profiles were generated for road functional classes and vehicle classes. Weight data for minor collectors and local roads were inadequate and did not provide 24-h vehicle weight distributions. So, hourly vehicle weight profiles for rural major collectors and urban minor arterial roads were used for rural minor collectors and local roads and for urban collectors and local roads. Because vehicle weights were provided for FHWA truck classes, EPA vehicle classes were assigned into FHWA truck classes through the X-classification scheme. Double-unit, 3- or 4-axle trucks (FHWA truck class 8) were separated with the 3-axle/4-axle ratio of 0.12 into X2 and X3A classes (Yoon et al., 2004). For weights by road type, vehicle class, and hour of day, measured vehicle volumes were multiplied by each weight bin and divided by total measured hourly volumes. Because 2-axle trucks correspond to EPA HDDV2b to 7 and their weights can not be separated into each EPA HDDV classes properly, the highest weight category bins in Lindhjem's (2004) weight data for each EPA HDDV class were used for their vehicle weights. Weight category bin values of 9,500, 12,000, 15,000, 17,750, 22,750, and 29,500 lbs were assigned to HDDV2b, HDDV3, HDDV4, HDDV5, HDDV6, and HDDV7 classes, respectively.

Auxiliary Power

Estimated auxiliary power demand for on-road vehicle operations was obtained from the SAE 2004 Automotive Handbook (SAE, 2004). The SAE Handbook provides typical auxiliary power demand for various accessories, but only for heavy HDVs and buses. Auxiliary power demand for each accessory was classified by season (winter and summer) and by time of day (day and night). Months from November to April were assigned to winter, and the other months were assigned to summer. Daytime is assumed to be from 9 a.m. to 5 p.m. during winter months and 8 a.m. to 6 p.m. during summer months. However, because the SAE Handbook does not provide light and medium HDV auxiliary power requirements, the research team used U.S. DOE study results (U.S. DOE, 2000), which indicate that a typical medium HDV requires approximately 50% of heavy HDV auxiliary power. Therefore, 50% of heavy HDV auxiliary power demand was used for light and medium HDDV auxiliary power demand.

Environmental Conditions

Hourly temperatures and atmospheric pressures were created for the calculation of air density. Hourly environmental parameters observed at Atlanta Hartsfield International Airport Meteorology Station from 2002 and 2004 were downloaded from National Climatic Data Center (NCDC, 2004). All same-month and hour data points were summed and then divided by the total number of data points to create a set of 3-year average hourly temperatures and atmospheric pressures.

Vehicle Frontal Areas and Aerodynamic Drag Coefficients

Typical vehicle frontal areas for EPA HDDV classes were estimated using vehicle specifications published by vehicle manufacturers (Truck Index, 1997). The research team investigated typical vehicle front and side shapes and assigned typical aerodynamic drag coefficients to each vehicle class. Due to the lack of vehicle configuration data (bobtail, single-unit, trailer, double trailer, tanker, flat-top, etc.), a single aerodynamic drag coefficient for each vehicle class was used (in later model versions, multiple configurations could be accommodated). Table 3 shows the typical vehicle frontal areas and aerodynamic drag coefficients.

Table 3. Typical Vehicle Frontal Areas and Aerodynamic Drag Coefficients.

X Class	EPA Class	Frontal Area (ft^2)	Aerodynamic Drag Coefficient
X1A	HDDV2b	26.2	0.45
	HDDV3	28.3	0.45
	HDDV4	26.7	0.45
	HDDV5	37.5	0.45
X1B	HDDV6	40.6	0.60
	HDDV7	44.0	0.60
X2A	HDDV8a	46.3	0.99
X2B	HDDV8a	46.3	0.99
X3A	HDDV8b	51.0	0.99
X3B	HDDV8B	51.0	0.99
X4	SCHBUS	80.0	1.17
X5	URBUS	80.0	1.17

Effective Inertia

For the estimation of drive train inertial loss (required for acceleration of moving engine and transmission parts as well as the axles and tires), the research team used vehicle speed and engine speed (revolution per minute, or rpm) data from EPA HDV test results (U.S. EPA, 2001a) to approximate combined transmissions gear ratio and differential gear ratio. For wheel and engine inertia, typical inertia values suggested by Gillespie (2004) were used. For transmissions and drive train inertia values, the research team used basic information from a parts manufacturer (ZELU, 2004). The inertia values suggested by ZELU were assigned into each EPA HDV classes using vehicle information obtained from the Diesel Truck Index (Truck Index, 1997). Tire radius data for each HDDV class were also obtained from the Diesel Truck Index. Table 4 shows typical rotational inertia for parts.

Table 4. Typical Tire Radius and Inertia Values.

EPA Class	Tire Radius (ft)	Rotational Inertia			
		Wheel (I_W)	Engine (I_E)	Trans-mission (I_T)	Drive Train (I_D)
HDDV2b	0.95	6.0	2.0	0.93	0.93
HDDV3/4/5	1.00	8.0	2.0	0.93	0.93
HDDV6/7	1.25	15.7	2.0	1.73	1.73
HDDV8a	1.30	15.7	2.0	2.46	2.46
HDDV8b	1.30	15.7	2.0	2.46	2.46
SCHBUS	1.30	15.7	2.0	2.46	2.46
URBUS	1.30	15.7	2.0	2.46	2.46

These values will be significantly improved and refined as new data become available from on-road vehicle and in-laboratory drive train testing.

Emission Rate Module

In the emission rate module, baseline diesel emission rates for each engine certification group are aggregated according to diesel registration fractions and annual mileage accumulation rates by vehicle age (Figure 7). Each zero-mile emission rate is multiplied by the diesel registration fraction by vehicle age, and each deterioration emission rate is multiplied by the diesel registration fraction and by the annual mileage accumulation rate by vehicle age. Twenty-five weighted zero-mile emission rates and deterioration emission rates are aggregated to a calendar year emission rate (Equation 4).

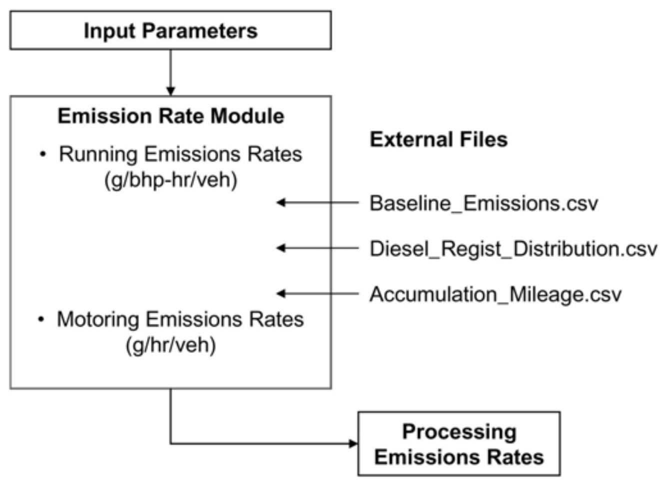

Figure 7. Emission Rate Module Process.

$$ER_v = \sum_{y=0}^{24}\left[\left(ZML_{v,y} \times DRF_{v,y}\right) + \left(DET_{v,y} \times DRF_{v,y} \times AMR_{v,y}\right)\right] \quad (4)$$

where ER is the emission rate in grams per brake-horsepower-hour,
v is the vehicle technology group,
y is the vehicle age,
ZML is the baseline zero-mile emissions rate in grams per brake-horsepower-hour,
DRF is the diesel vehicle registration fraction by vehicle age,
DET is the baseline deterioration emissions rate in grams per brake-horsepower-hour per 10,000 mile, and
AMR is the annual mileage accumulation rate in miles per 10,000miles.

Emission rates for motoring (absorbing power as the vehicle and engine slow) are set to idle, and emission rates for vehicle idling are obtained from the data set used by the California Air Resources Board (CARB) in the development of EMFAC2002 emission rates (CARB, 2004). Baseline idling emission rates for each vehicle type and model year are multiplied by the diesel vehicle registration fraction for each year. The twenty-five idle emission rates are then aggregated for each calendar year to create a diesel vehicle idling (or motoring) emission rate for each vehicle type (Equation 5).

$$MER_v = \sum_{y=0}^{24}\left(IDL_{v,y} \times DRF_{v,y}\right) \quad (5)$$

where MER is the idling (or motoring) emission rate in grams per hour, and
IDL is the baseline idling emission rate in grams per hour.

Table 5. Example Baseline Emission Rates for Year 1980 and 2004.

X Class	EPA Class	HP Range	Model Year	HC_ZML (g/bhp-h/veh)	HC_DET (g/bhp-h/veh)	HC_IDL (g/h/veh)
X1A	HDDV2b, HDDV3, HDDV4, HDDV5	70–170	1980	0.664	0.002	23
			2004	0.140	0.001	8
X1B	HDDV6, HDDV7	170–250	1980	0.660	0.002	23
			2004	0.170	0.001	8
X2A	HDDV8a	250+	1980	0.470	0.001	23
			2004	0.170	0.001	8
X2B	HDDV8a	250+	1980	0.470	0.001	23
			2004	0.170	0.001	8
X3A	HDDV8b	250+	1980	0.470	0.001	23
			2004	0.170	0.001	8
X3B	HDDV8b	250+	1980	0.470	0.001	23
			2004	0.170	0.001	8
X4	SCHBUS		1980	0.660	0.002	23
			2004	0.170	0.001	8
X5	URBUS		1980	0.470	0.001	23
			2004	0.080	0.000	8

Baseline Diesel Emission Rates

Baseline diesel emission rates (grams per brake-horsepower-hour) for each engine certification group are derived from the EPA engine dynamometer test results used in the MOBILE6.2 emission rate model development (U.S. EPA, 2002). As indicated above, because EPA does not provide idling emission rates by engine age group or engine certification group, idling emission rates (grams per hour) are obtained from chassis dynamometer test results, which were used for the EMFAC2002 model (CARB, 2004). As an example, Table 5 shows hydrocarbon baseline emission rates obtained from the MOBILE6.2 and EMFAC2002.

Diesel Registration Fractions

Diesel registration fractions are calculated from default diesel fractions and default registration fractions (sum of gasoline and diesel vehicles) for each vehicle type and age, which were used in MOBILE6.2 (U.S. EPA, 2001b). Each calendar year's diesel fraction is multiplied by the corresponding year registration fractions. To calculate diesel registration fractions, diesel fractions multiplied by registration fractions are normalized for each vehicle class (Table 6).

Table 6. Example of Normalized Diesel Registration Fractions.

Age	EPA Class	HDDV2b Regis. Fraction	Diesel Fraction	Sum of Diesel Fraction	Normal. Diesel Regis. Fraction
0	HDDV2b	0.046	0.200	0.223	0.042
1	HDDV2b	0.059	0.258		0.069
Rest of data not shown for brevity					
24	HDDV2b	0.000	0.000		0.000

Annual Mileage Accumulation Rates

For the estimation of calendar year deterioration emissions rates, MOBILE6.2 default annual mileage accumulation rates are used for the annual mileage accumulation rates (U.S. EPA, 2001b). The default annual mileage accumulation rates are used without the correction of off-cycle effect.

Processing Link-Based Emissions and Air Toxics Ratios

Baseline zero-mile emission rates, baseline deterioration emission rates, tractive engine power, motoring fraction, running vehicle volume, and motoring vehicle activity estimated from the three modules are incorporated to estimate emissions (grams per hour) for HC, CO, NO_X, and PM (Equation 6, Figure 8).

$$HE_v = \left(VA_v \times P_v \times ER_v\right) + \left(MVA_v \times MER_v\right) \quad (6)$$

where *HE* is the estimated hourly emissions from a vehicle class a link in grams per hour,
VA is the estimated vehicle activity in vehicle-hour per hour,
P is the engine power demand in brake horsepower,
ER is the work-related emission rate in grams per brake horsepower-hour,
MVA is the motoring vehicle activity in vehicle-hour per hour, and
MER is the motoring (idling) emission rate in grams per hour.

From the estimated HC emissions, air toxic emissions are also estimated by multiplying the ratios of air toxics to HC for each calendar year. Air toxics include benzene (BENZ), 1,3-butadiene (BUTA), formaldehyde (FORM), acetaldehyde (ACET), and acrolein (ACRO). To develop the ratios of air toxics to HC, the research team ran MOBILE6.2 from calendar year 1995 to 2020 with Atlanta air quality planning region default modeling parameters. Each of the five air toxic emissions rates was divided by HC emissions rates for each calendar year. Estimated ratios were directly multiplied to hourly modal emission rates estimated with the interim outputs from the three modules (see Equation 6).

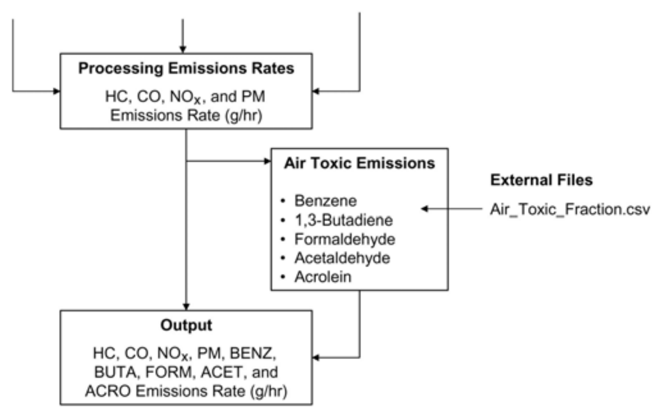

Figure 8. HC, CO, NO_X, PM, and Air Toxic Emissions Estimation Process.

Model Outputs

Output file names are automatically created using the pre-defined modeling options such as INPUT_Road_Segment file name, county code, calendar year, modeling month, and modeling hour (i.e., "Atlanta_Downtown.csv_121_2004_7_7.csv"). Output files contain road characteristic information taken from HPMS information and estimated link-based emissions for each pollutant and for each vehicle type. Table 7 shows an example output file for HC emissions rates.

Output files contain not only hourly emissions for each pollutant and for each vehicle, as well as roadway characteristic information such as county codes, state roadway codes, link identifications by mile point, roadway classifications, and so forth. Positive roadway identification can be used to import link-based emissions for regional or county level emission inventories and for use in local level air quality impact assessment. For instance, county-level emissions inventory data can be readily developed by aggregating emissions across county link identification codes. Local air quality impact assessment analyses can be undertaken by extracting the hourly emissions from specified roadway links identified by State DOT Roadway Characteristic Link ID and mile-point. For spatial and temporal emissions analysis, output files are connected to the original GIS roadway network through the creation of unique link identifiers. Using rclink IDs and link mile-points, unique link IDs can be created and joined back into the GIS roadway networks. Appendix A shows the how the results can be transferred back to the GIS interfaced to view emissions analysis results.

Table 7. An Example Output File for HC Emissions.

CNTY	RcLink	—	HC2b	HC3	—	HC8a	HCX3A	HCX3B	HCX4
121	1211–	—	2.10	0.08	—	0.18	0.42	1.03	0.00
121	1211–	—	0.22	0.01	—	0.06	0.06	0.09	0.00
121	1211–	—	0.55	0.02	—	0.05	0.11	0.27	0.00
121	1211–	—	0.75	0.02	—	0.05	0.21	0.21	0.00
Rest of data not shown for brevity.									
121	1211–	—	7.29	0.28	—	0.65	1.46	3.60	0.00

Conclusions

Over the next year, the research team will be evaluating the sensitivity of the HDDV-MEM and evaluating additional sources of data that can be used to refine the model. The HDDV-MEM uses several rule-of-thumb parameters and assumed criteria such as motoring activity, inertial loads, coefficients related to vehicle characteristics, and so forth, which may yield significant changes in emissions predictions when input data are improved. The model sensitivity analysis will identify the model parameters that are the most important to improve first.

Although the HDDV-MEM has uncertainties at the current stage of development, this model has outstanding potential for applications of mobile source emissions inventory development and microscale air quality assessment only if parameters causing uncertainties are examined and improved. For the examination and improvement of the HDDV-MEM, extensive data should be collected such as on-road emissions data as a function of engine load, vehicle technology subgroup development (data and statistical grouping), modal activity characterization, and so forth.

References

Ahanotu, D. (1999). Heavy-Duty Vehicle Weight and Horsepower Distributions: Measurement of Class-specific Temporal and Spatial, Thesis, Georgia Institute of Technology.

CARB (2004). Development of Idling Emissions Factors (http://www.arb.ca.gov/regact/hdvidle/appc.doc), California Air Resources Board.

Feng, C., S. Yoon, and R. Guensler (2005). Data Needs for a Proposed Modal Heavy-Duty Diesel Vehicle Emission Model, Proceedings of the 97th Air and Waste Management Association Annual Meeting, Minneapolis, MN.

GDOT (2004a). Georgia Statewide Highway Performance Monitoring System, Georgia Department of Transportation.

GDOT (2004b). Georgia GIS Clearinghouse, Map Data & Aerial Photography (http://gis.dot.state.ga.us/), Georgia Department of Transportation.

Gillespie, T (1992). *Fundamentals of Vehicle Dynamics*, ISBN 1-56091-199-9, Society of Automotive Engineers, Inc., Warrendale, PA.

Gillespie, T (2004). Typical inertia values for wheel and engine, Personal communication, November, 2004.

Grant, C. (1998). Modeling Speed/Acceleration Profiles on Freeways, Thesis, Georgia Institute of Technology.

Guensler, R., K. Dixon, V. Elango, and S. Yoon (2004). MOBILE-Matrix: Georgia Statewide MTPT Application for Rural Areas, *Transportation Research Record: Journal of Transportation Research Board*, No. 1880, Transportation Research Board, National Research Council, Washington, DC, pp. 83-89.

Guensler, R., S. Yoon, C. Feng, H. Li, and J. Jun (2005). Heavy-Duty Diesel Vehicle Modal Emission Model (HDDV-MEM): Volume I: Modal Emission Modeling Framework, EPA-600/R-05/090a, U.S. Environmental Protection Agency, Washington, DC.

Lindhjem, C., and S. Stella (2004). Development Work for Improved Heavy-Duty Vehicle Modeling Capability Data Mining-FHWA Datasets, Phase II: Final Report, ENVIRON International Corporation, Novato, CA.

NCDC (2004). National Climate Date Center, Atlanta Hartsfield International Airport (Atlanta, Georgia) (http://www.ncdc.noaa.gov/oa/ncdc.html) (accessed August 2005).

SAE (2004). Information Relating to Duty Cycles and Average Power Requirement of Truck and Bus Engine Accessories, SAE J1343 (August 2000). Society of Automotive Engineers, Inc., Warrendale, PA.

Truck Index (1997). 1997 Diesel Truck Index, Truck Index, Inc.

U.S. DOE (2000). Technology Roadmap for the 21st Century Truck Program, 21CT-001, Oak Ridge National Laboratory, U.S. Department of Energy.

U.S. EPA (2001a). Heavy Duty Diesel Fine Particulate Matter Emissions: Development and Application of On-Road Measurement Capabilities, EPA-600/R-01/079 (NTIS PB2002-100140), National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Washington, DC.

U.S. EPA (2001b). Fleet Characterization Data for MOBILE6.2, EPA-420/R-01/047, Office of Transportation and Air Quality, U.S. Environmental

Protection Agency, Washington, DC.

U.S. EPA (2002). Update of Heavy-Duty Emission Levels (Model Years 1998–2004+) for Use in MOBILE6.2, EPA-420/R-02/018, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, DC.

U.S. EPA (2004). EPA Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles, 40CFR86 Appendix I (c). U.S. Government Printing Office, Washington, DC.

Yoon, S., P. Zhang, J. Pearson, R. Guensler, and M. Rodgers (2004). A Heavy-Duty Vehicle Visual Classification Scheme: Heavy-Duty Vehicle Reclassification Method for Mobile Source Emissions Inventory Development. Proceedings of the 97th AWMA Annual Meeting. Indianapolis, IN.

Yoon, S., H. Li, J. Jun, R. Guensler, and M. Rodgers (2005a). Transit Bus Engine Power Simulation: Comparison of Speed-Acceleration-Road Grade Matrices to Second-by-Second Speed, Acceleration, and Road Grade Data. Proceedings of the 97th Air and Waste Management Association Annual Meeting, Minneapolis, MN.

Yoon, S. (2005b). A New Heavy-Duty Vehicle Visual Classification and Activity Estimation Method for Regional Mobile Source Emissions Modeling, Thesis, Georgia Institute of Technology.

Yoon, S., H. Li, J. Jun, J. Ogle, R. Guensler, and M. Rodgers (2005c). A Methodology for Developing Transit Bus Speed-Acceleration Matrices to be Used in Load-Based Mobile Source Emissions Models, *Transportation Research Record: Journal of Transportation Research Board*, Transportation Research Board, National Research Council, Washington, D.C. (in Press).

ZELU (2004). Industrias Zelu,S.L. Inertia values for rotating transmissions and drive trains (http://www.navarrainfo.com/zelu/application.htm)

Appendix A: Link-Based HDDV-MEM Modeling Results on the GIS Roadway Network

The heavy-duty diesel vehicle modal emission model (HDDV-MEM) was run for a portion of the Atlanta downtown area along I-75/I-85 downtown connector. Figure A-1 shows the selected roadway links (green links in the red rectangle) inside I-285 circle and links in the middle of downtown (brown links in the blue rectangle).

The selected areas consisted of 3,853 roadway links, and the HDDV-MEM model processing time per link was approximately 2.5 seconds on a Pentium IV 2.4GHz PC with 768 RAM. Four one-hour scenarios were run (7 A.M, 12 P.M., 5 P.M., and 10 P.M). When the process was completed, a unique link ID for each link was created for joining into the original roadway network feature in GIS shape file format. The road characteristic link identification number (RcLinkID), the start mile point, and the end mile point for a link were combined as a unique link ID and used in the joining process. After joining the modeling output to the roadway feature, the feature was converted into 10 meter by 10 meter grid raster data with emission values for each pollutant. Figures A-2 and A-3 show NO_X emissions in grams/hour for the four time periods on selected roadway links.

As shown in Figures A-2 and A-3, roadway links on the I-75/I-85 downtown connector show higher NO_X emissions than other arterial or local roads. That resulted from those roadway links downtown experiencing much higher HDDV volumes than other roadway links during the simulation time periods.

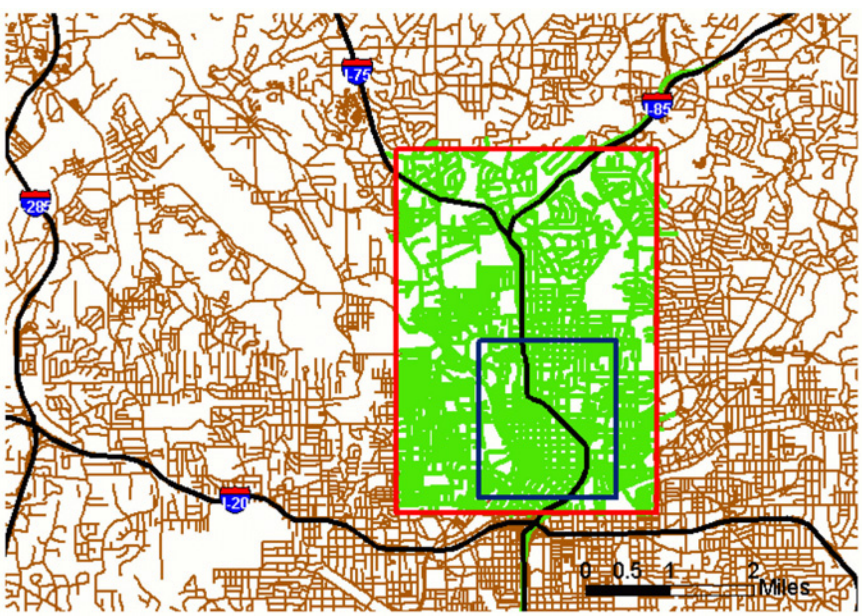

Figure A-1. HDDV-MEM Modeling Area (inside of Red Box) in Downtown Atlanta, GA.

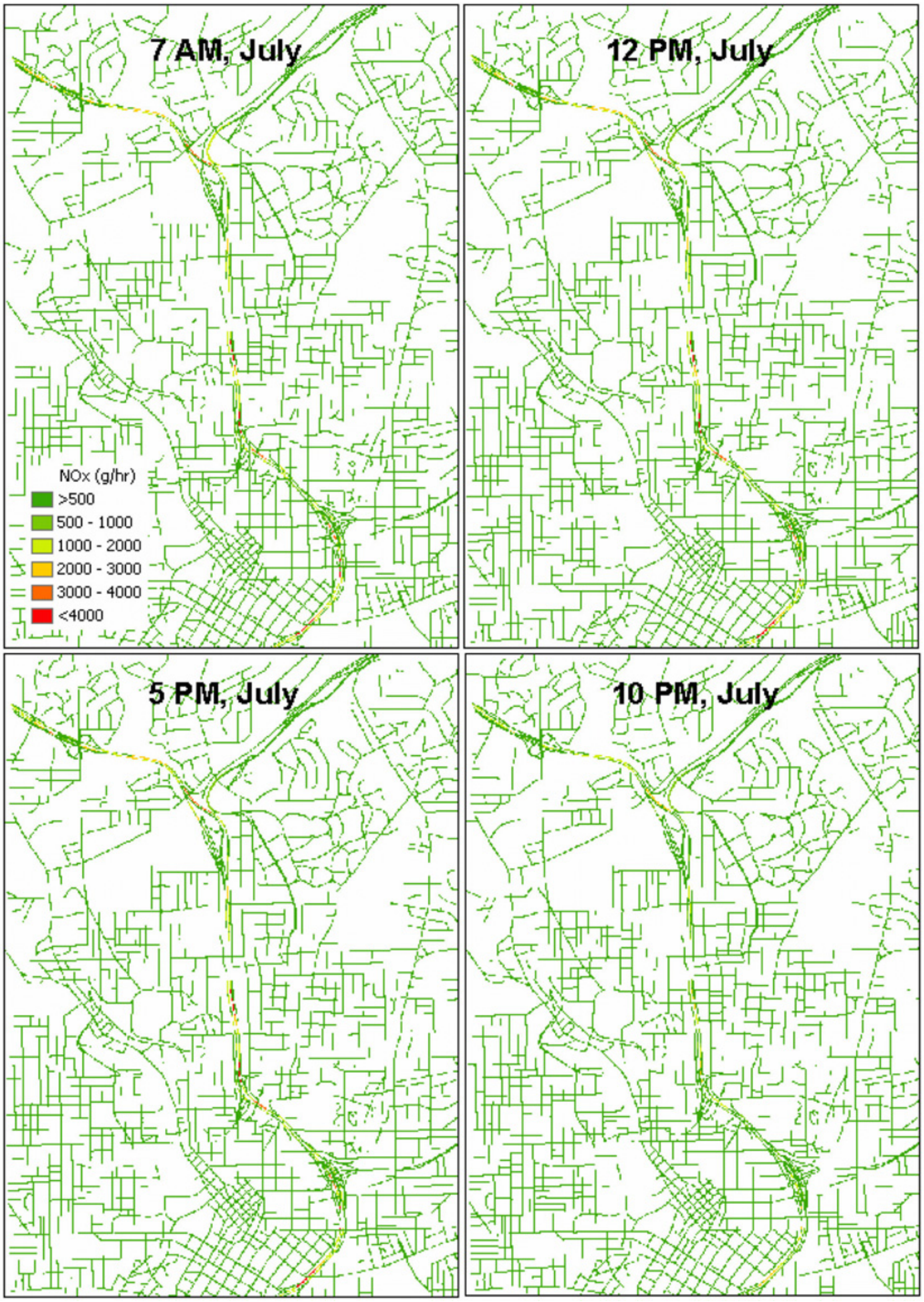

Figure A-2. NO_x Emissions (g/hr) on Selected Links (Red Rectangle) Inside I-285.

Figure A-3. NO_X Emissions (g/hr) on Links (Blue Rectangle) in Downtown Atlanta, GA.

Appendix B: HDDV-MEM System Operations

The heavy-duty diesel vehicle modal emission model (HDDV-MEM) estimates hourly emissions for each simulated roadway segment. The time required to estimate hourly emissions for a single road segment is approximately 2.5 seconds on a computer equipped with a Pentium IV 2.4GHz CPU and 768 RAM. HDDV-MEM estimates emissions using a set of modeling algorithms calling data from tables containing a variety of model parameters (in forms of internal data or external data files). Internal data tables contain vehicle configuration information (frontal areas in square feet, aerodynamic drag coefficients, and so forth), road surface coefficients, and other hard-coded data. External data files contain information associated with vehicle activity, roadway characteristics, environmental conditions, and other user-defined variables. External data files include:

- Speed/acceleration matrices,
- Weight distributions,
- Environmental parameters,
- Auxiliary power demand,
- VMT distributions,
- Hourly VMT profiles,
- Diesel fraction,
- Effective inertia,
- Baseline emissions rates,
- Diesel registration distributions,
- Accumulation mileage rates,
- Air toxic emissions fractions, and
- Roadway characteristics.

The model is an ASPEN Perl executable and does not yet have a true graphic user interface. Before running the HDDV-MEM, “HDDVMEM_V1.pl” all 13 external files and should be in the same folder, and ASPEN Perl version 5.6 or higher version should be installed. The MATH::ROUND Perl extension must be installed before executing the model. This extension, “round.pm” should be in folder C:\Perl\lib\Math. The “round.pm” extension supplies functions that will round numbers in various ways. The HDDV-MEM will be activated by double-clicking the “HDDVMEM_V1.pl”. Then, a DOS window will ask for the following:

- Modeling region (identified by FIPS code, see Table B-1),
- Modeling year,
- Modeling month,
- Modeling hour, and
- Roadway characteristics file name .

Once all modeling parameters are entered, the HDDV-MEM starts calculating hourly emissions from each segment listed in the roadway characteristics file. If “ALL” is typed for the modeling hour on the DOS window, daily emissions aggregated hourly emissions will be outputted. Figure B-1 shows an example of model execution window. If a user desires to estimate emissions for an entire a region, users provide roadway characteristics files in the same format with the roadway characteristics files in the regional model.

Table B-1. FIPS Codes for 13 Atlanta Metropolitan Area Counties.

County Name	FIPS Code
Cherokee	57
Clayton	63
Cobb	67
Coweta	77
De Kalb	89
Douglas	97
Fayette	113
Forsyth	117
Fulton	121
Gwinnett	135
Henry	151
Paulding	223
Rockdale	247

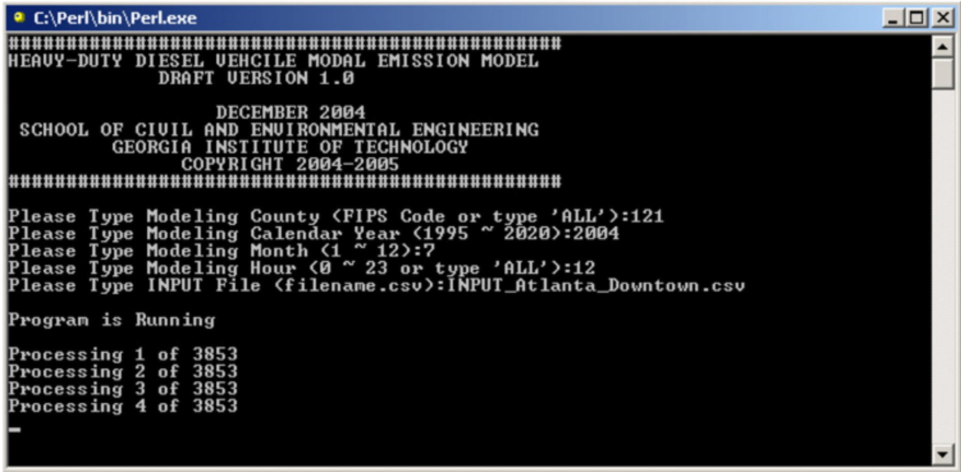

Figure B-1. Example View of the HDDV-MEM Running Window.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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16. ABSTRACT
The report outlines research of a proposed heavy-duty Diesel vehicle modal emission modeling framework (HDDV-MEMF) for heavy-duty diesel-powered trucks and buses. Although the heavy-duty vehicle modal modules being developed under this research are different from the motor vehicle emissions simulator (MOVES) model, the HDDV-MEMF modules should be compatible with MOVES. In the proposed HDDV-MEMF, emissions from heavy-duty vehicles are predicted as a function of hours of on-road operation at specific engine horsepower loads. Hence, the basic algorithms and matrix calculations in the new heavy-duty diesel vehicle modeling framework should be transferable to MOVES. The specific implementation approach employed by the research team to test the model in Atlanta is somewhat different from other approaches in that an existing geographic information system (GIS) based modeling tool is being adapted to the task. The new model implementation is similar in general structure to the previous modal emission rate model known as the mobile assessment system for urban and regional evaluation (MEASURE) model. This exploratory framework is designed to be applied to a variety of policy assessments, including those aimed at reducing the emission rates from heavy-duty vehicles and those designed to change the on-road operating characteristics to reduce emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Pollution Control	13B
Highway Transportation	Stationary Sources	15E
Trucks		13F
Buses (vehicles)		
Emissions		14G
Transportation Models		12A

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