Journal of Traffic and Transportation Engineering(English Edition)
2014,1(2):81-96

Sensitivity analysis of project level MOVES running emission rates for light and heavy duty vehicles

Zhuo Yao[1], Heng Wei[1,*], Harikishan Perugu[1], Hao Liu[1], Zhixia Li[2]

[1] *ART-Engines Transportation Research Laboratory, College of Engineering and Applied Science, University of Cincinnati, Cincinnati, OH, USA*

[2] *Traffic Operations and Safety (TOPS) Laboratory, College of Engineering, University of Wisconsin-Madison, Madison, WI, USA*

Abstract: In order to understand how the uncertainties in the output can be apportioned to different sources of uncertainties in its inputs, it is critical to investigate the sensitivity of MOVES model. The MOVES model sensitivity for regional level has been well studied. However, the uncertainty analysis for project level running emissions has not been well understood. In this research, the MOVES model project level sensitivity tests on running emissions were conducted thru the analysis of vehicle specific power (VSP), scaled tractive power (STP), and MOVES emission rates versus speed curves. This study tested the speed, acceleration, and grade-three most critical variables for vehicle specific power for light duty vehicles and scaled tractive power for heavy duty vehicles. For the testing of STP, four regulatory classes of heavy duty vehicles including light heavy duty (LHD), medium heavy duty (MHD), heavy heavy duty (HHD) and bus were selected. MOVES project running emission rates were also tested for CO, PM2.5, NO_x, and VOC versus the operating speeds. A Latin Hypercube (LH) sampling based on method for estimation of the "Sobal" sensitivity indices shows that the speed is the most critical variable among the three inputs for both VSP and STP. Acceleration and grades show lower response to the main effects and sensitivity indices. MOVES emission rates versus speeds curves for light duty vehicles show that highest emission occurs at lower speed range. No significant differences on emission rates among the regulatory classes of heavy duty vehicles are identified.

Key words: MOVES model; sensitivity analysis; project level; emission rates

1 Introduction

The motor vehicle emission simulator (MOVES) developed by U. S. Environmental Protection Agency (U. S. EPA) Office of Transportation and Air Quality (OTAQ) is a new emission modeling system esti-

* **Corresponding author**: Heng Wei, PhD, P. E., Associate Professor.
E-mail: heng.wei@uc.edu.

mating emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis (U. S. EPA 2013). It is now required that the MOVES model will be used for state implementation plan (SIP) and conformity purposes (U. S. EPA 2012a). In order to understand how the uncertainty in the output can be apportioned to different sources of uncertainty in its inputs, it is critical to test the MOVES model performance and sensitivity.

The MOVES regional sensitivity study has been performed by the Volpe National Transportation Systems Center at Federal Highway Administration (FHWA). It was conducted at regional and county scale and focused on the running emissions process for carbon monoxide (CO), oxides of nitrogen (NO_x), particulate matter of less than 2.5 micrometers (PM2.5), and volatile organic compounds (VOCs). The parameters evaluated by the study are temperature, humidity, ramp fraction, age distribution and average speed distribution. This study shows the order of impact on vehicle emissions by using actual data is average speed distributions, vehicle age distributions and ramp fractions (Noel and Wayson 2012). As anticipated, vehicle fleet and activity data are the most sensitive inputs for the model since the MOVES model utilizes the vehicle specific power (VSP) approach which considers the instantaneous engine power outputs as a key factor for emission modeling (U. S EPA 2011; 2012b). Federal Highway Administration resource center also entrusted AECOM for MOVES sensitivity study and comparison of MOVES, MOBILE 6.2 and EMFAC. Thru those studies, they concluded that the MOVES emission rates are very sensitive to speed, as well as source types and ages (Hawk 2009). They also observed that using less refined inputs would result in higher emissions. Texas Transportation Institute also reported their testing results for MOVES sensitivity. They simulated the effects of control programs, such as inspection and maintenance (I/M) programs, gasoline Reid vapor pressure (RVP) and sulfur content effects, as well as meteorological inputs including temperature, relative humidity and barometric pressure. Moreover, the testing of influences of vehicle fleet characteristics and vehicle speed is also performed. The study presented comparative results from previously defined scenarios and the emission rates used were also from look-up tables derived from county scale MOVES results. However, the MOVES sensitivity analysis under project level has not been carefully studied although the key of MOVES model, vehicle specific power, is usually calculated based on trajectories of individual vehicles.

At project emission modeling scale, previous studies (Boriboonsomsin and Barth 2009; Fernandez and Long 1995; Hallmark et al. 2002; Park and Rakha 2005) have shown that roadway grade has a significant impact on the emissions even before MOVES model was released. Empirical results show that the magnitude of significance ranges from 50% up to 200% depending on the type of pollutant and corresponding roadway grade. The results have lots of uncertainties since there is evidence of a synergistic effect of grade and speed, and a potential load threshold for emission excursions as well. Since the grade plays such a critical role in emission modeling, it is imperative to further understand the MOVES model's elasticity on roadway grade. Since the MOVES model adopts the VSP approach, which considers the grade as a variable, it is important to know how MOVES model response to the changes in grade and its corresponding VSP. Especially, to what extend will the grade impact the emissions has rarely been recognized and recommendations to the practices of using MOVES model at project level when roadway grade influences should be made.

A summary of the studies on project level impacts on emissions is first presented, followed by a description of the methodology and parameters used in this study. Sensitivity tests on the VSP and STP, and the MOVES emission rates on speed are then quested. Next, results of the sensitivity tests are given. Finally, a summary, conclusion, and recommendations for further research are provided.

2 Summary of existing studies

It is commonly recognized that emissions tend to increase when vehicles are traveling uphill than on a flat surface road since the engine needs to produce more power to work against the gravity. On the other hand, the emissions should be lower since the gravity acts as a driving force. The magnitude of the impact of grade differences on emissions has been studied since the 1990s. Fernandez and Long (1995) studied the grades effects on on-road emissions by using on-board analyzer. They compared emissions from uphill on grades ranging from 0 to 7%. As a reference of the grade impact, they compared their monitored results with the EMFAC speed correction factor corrected emission rates. They found when grades were above 3%, hydrocarbon and CO emissions were higher than the model predictions. While results from negative grades or flat terrain were quite close to the predicted values. Even more, they observed that the increment of 1% grade would result in 3.0 grams/mile of CO emissions.

However, in practice, it is critical to obtain the roadway grade inventory and use it for emission estimation and modeling. Zhang and Frey (2005) proposed a method for estimating road grade based upon bivariate regression using light detection and ranging (LIDAR) data. The implications of accurate estimation of road grade with respect to emissions estimation were investigated based upon calculation of total emissions of NO_x, CO, hydrocarbons, and CO_2. Park and Rakha (2005) studied the energy and environmental impacts of roadway grades using microscopic simulation software. The study demonstrates that the impact of roadway grade is significant with increases in vehicle fuel consumption and emission rates in excess of 9% for a 1% increase in roadway grade. Consequently, a reduction in roadway grades in the range of 1% can offer benefits that are equivalent to various forms of advanced traffic management systems. However, since the microscopic simulation model itself has an energy and emission component which is completely different from the MOVES modeling approach, the results and recommendations may not be necessarily adaptable to current practice. Boriboonsomsin and Barth (2009) conducted research on impacts of road grade on fuel consumption and carbon dioxide emissions using the comprehensive modal emission model (CMEM). Their results show that road grade does have significant impacts on the fuel economy of light-duty vehicles both at the roadway link level and at the route level. They reported that the overall fuel economy of the flat route is superior to that of the hilly route by approximately 15% to 20% based on the combined model and empirical study for light-duty vehicles.

Little research effort has been made to the sensitivity testing on project level MOVES modeling. Vallamsundar and Lin (2013) did sensitivity study of MOVES and AERMOD in corresponding to the EPA's requirment regarding PM2.5 hotspot analysis. The study found MOVES PM2.5 EFs are most sensitive to speed compared to other input parameters and EFs are highest when vehicles are idling. Emissions from gasoline powered vehicles were found to be more sensitive to seasonal, daily and yearly variations compared to diesel powered vehicles. Therefore, there is a gap between research on the traffic activity impacts to emissions and how MOVES model reacts to the changes in speed, acceleration and grades.

This paper extends previous work by further recognizing MOVES project level running emissions elasticity in three ways: (a) perform sensitivity tests on VSP and STP for multiple MOVES link source types; (b) compare the magnitude of emission differences when roadway grade is included with zero grades results; (c) recommend best practices for MOVES project level emission analysis.

3 Methodology

The specific aim of this research is to test the sensitivity of MOVES model in terms of roadway grades on emissions. To accomplish this, two objectives are designated to fulfill: (1) to perform sensitivity analysis of the VSP approached based binning system; (2) to compare the MOVES results when grades are included with the assumed zero grades. In this project, the case study will focus on the running emissions process for CO, PM2.5, NO_x, and VOCs as studied in the regional level MOVES sensitivity performed by FHWA (Noel 2013).

3.1 Grade data collection

To fulfill the objectives, a set of second-by-second GPS data was collected. Almost 110000 records of data were collected in this study on the 30 km interstate freeway. A data filter with high horizontal dilution of precision (HDOP) greater than 4 and low NSAT less than 4 (Gong et al. 2012) was applied to remove invalid data due to blocking of satellite signals. The handheld GPS data loggers used is Qstarz BT-Q1000EX. They were set to collect variables including date, time, latitude, longitude, altitude, speed, HDOP and number of satellites (NSAT) used, etc. According to the specifications of the manufacture (Qstarz 2012), the device error is less than 3 meters for positioning and 0.1 m/s for measuring velocity.

The horizontal run is calculated by using the haversine formula. It is a method to calculate the shortest distance over the earth's surface by assuming that the trajectory traveled between two consecutive sets of latitude and longitude is a straight line. The so-called great circle distance between two points remains particularly well-conditioned for numerical computation even at small distances (Movable Type Scripts 2012).

$$a = \sin^2\left(\frac{Lat_{n+1} - Lat_n}{2}\right) + \cos(Lat_n) \times \cos(Lat_{n+1})\sin^2\left(\frac{Long_{n+1} - Long_n}{2}\right) \quad (1)$$

$$Run = 2R \times \mathrm{atan2}(\sqrt{a}, \sqrt{1-a}) \quad (2)$$

where *Lat* is latitude; *Long* is longitude; *R* is radius of earth (mean value is 6371 km).

Then the freeway grade was calculated. The samples collected shows that 92.35% grade data falls into the range of −10% and 10%. A total of 92914 grade data points are obtained. There is merely any data point with grade equals to zero. This shows that for VSP based emission and energy consumption modeling, the zero grade is rarely the case for urban interstate freeways in U. S. Based on data collected, 90.15% AM, 97.3% Mid-day and 92.01% PM data falls into a grade range of −6% to 6%. The distribution is almost perfect bell-curves of normal distribution. Therefore, the selection of grade range between −6% to 6% is justified and is a well representation of the typical urban freeway.

3.2 Speed and acceleration/deceleration rate ranges

The vehicle operating speed range of 0 to 90 mph is selected based on the results from Boriboonsomsin and Barth (2009). Although the study was for fuel consumption and carbon dioxide emissions, their results show that there is a sharp increasing of fuel consumption when speed is beyond 80 mph.

The maximum acceleration and deceleration rate which a vehicle could produce depends on the vehicle type, the level of terrain and the traveling speed. However, there is a range of acceptable acceleration rate that is commonly accepted. Tab. 1 shows the maximum acceleration (Acc) and deceleration (Dec) rates selected for this study based on recommendations from Federal Highway Administration (U. S. DOT 1994; FHWA 1998), Institute of Transportation Engineers (Pline 1999) and studies on microscopic simulations models (Yang 1997) and safety studies (Gates et al. 2007).

Tab. 1 Maximum acceleration and deceleration rates (ft/s^2)

Regulatory class	Speed (ft/s)									
	<20		20–40		40–60		60–80		≥80	
	Acc	Dec	Acc	Dec	Acc	Dec	Acc	Dec	Acc	Dec
Light duty vehicles (passenger cars)	10.00	11.20	7.90	9.50	5.60	9.00	4.00	8.50	4.00	8.00
Buses	7.00	5.00	5.00	5.00	4.00	5.00	1.50	5.00	1.00	5.00
Light and medium heavy duty	2.80	5.00	2.50	5.00	1.50	5.00	1.00	5.00	0.50	5.00
Heavy-heavy duty	1.60	5.00	1.45	5.00	0.89	5.00	0.47	5.00	0.40	5.00

The maximum deceleration rate, *a*, is set equal to 3.4 m/s^2 (11.2 ft/s^2) (Fancher and Gillespie 1997; Harwood et al. 1997). This value was found by Fambro et al. (1997) to represent the 10th percentile deceleration rate of passenger cars. This deceleration rate represents a comfortable value for controlled braking by a passenger car driver and is within the driver's capability to stay within his or her lane and maintain steering control when braking on wet surfaces.

3.3 VSP/STP and operating mode distribution

VSP is traditionally defined to represent the instantaneous vehicle engine power. It has been widely utilized to reveal the impact of vehicle operating conditions on emission and energy consumption estimates that are dependent upon the speed, roadway grade and acceleration or deceleration on second-by-second basis. Then the calculated VSP values are computed.

The VSP values for light duty vehicles are calculated by the following equation (Jimenez 1999):

$$\mathrm{VSP} = v \times [a(1+\xi) + g \times grade(\%) + g \times C_R] + 0.5\rho \times C_D \times A \times v^3/m \quad (3)$$

where v is vehicle speed (assuming no headwind) in m/s; a is vehicle acceleration in m/s^2; ξ is mass factor accounting for the rotational masses (about 0.1); g is acceleration due to gravity; *grade* is road grade; C_R is rolling resistance (about 0.0135); C_D is aerodynamic drag coefficient; A is the frontal area; m is vehicle mass in metric tonnes.

The equation can also have a vehicle accessory loading term (air conditioner being the most significant) added to it. Moreover, higher order terms in rolling resistance can be added to increase model accuracy (Gillespie 1992). Using typical value of coefficients ($C_D \times A/m$, about 0.0005), in SI units the equation becomes (Nam 2003):

$$\mathrm{VSP}\ (\mathrm{kW/metric\ ton}) = v \times [1.04a + 9.81 \times grade(\%) + 0.132] + 0.00121 \times v^3 \quad (4)$$

For heavy-duty vehicles, the STP is used. At a given time t, the instantaneous STP_t represents the vehicle's tractive power scaled by a constant factor. STP is calculated as a third-order polynomial in speed, with additional terms describing acceleration and road-grade effects. The coefficients for this expression, often called road load coefficients, factor in the tire rolling resistance, aerodynamic drag, and friction losses in the drivetrain.

The STP values for heavy duty vehicles are calculated by the following equation (Nam 2003a; U. S. EPA 2012):

$$\mathrm{STP}_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{f_{\mathrm{scale}}} \quad (5)$$

where A is rolling resistance coefficient (kW · s/m); B is rotational resistance coefficient (kW · s^2/m^2); C is the aerodynamic drag coefficient (kW · s^3/m^3); m is mass of vehicle (metric ton); f_{scale} is fixed mass factor; v_t is instantaneous vehicle velocity at time t (m/s); a_t is instantaneous vehicle acceleration (m/s^2).

The values of coefficients A, B, and C are the road load coefficients pertaining to the heavy-duty vehicles as determined through the EPA's physical emission rate estimator (PERE) (Nam 2003). Tab. 2 shows the coefficients of STP for different regulatory vehicle classes. Thus, the STP for each MOVES heavy duty vehicle regulatory class (from light duty to heavy duty and urban bus) is ready to perform the sensitivity test.

Tab. 2 STP coefficients

Regulatory class	Regulatory class name	Average running weight m (metric ton)	A	B	C	f_{scale}
LHD	Light-heavy duty	5.0	0.000226	0	1.470000024	2.06
MHD	Medium-heavy duty	11.4	0.000452	0	1.930000027	17.10
HHD	Heavy-heavy duty	27.7	0.000831	0	2.890000019	17.10
BUS	Urban Bus	16.6	0.000484	0	3.220000023	17.10

4 Results from sensitivity analysis

The sensitivity test presents results from testing speed, acceleration rate and roadway grade impacts on VSP for light duty vehicles, speed, acceleration rate on STP for heavy duty vehicles and vehicle operating speed on MOVES running emission rates.

4.1 VSP sensitivity analysis for light duty vehicles

The VSP was firstly studied by investigating its three-dimensional surface against acceleration rate and speed. Fig. 1 shows the 3D surface of VSP with a speed range of 0-90 mph and acceleration rate of −11 to 10 ft/s^2. The surface has a very sharp increasing when speed is above 40 mph. The simulation of the 3D surface VSP ranges from −80 to 4160 kW/metric ton. Although it covers only a small range of VSP from 0 to 30 kW/metric ton, the theoretical values of light duty vehicle VSP may range much higher. The extreme VSP value exists at the highest speed and highest acceleration rate as indicated in Fig. 1, the upper right corner of the 3D surface.

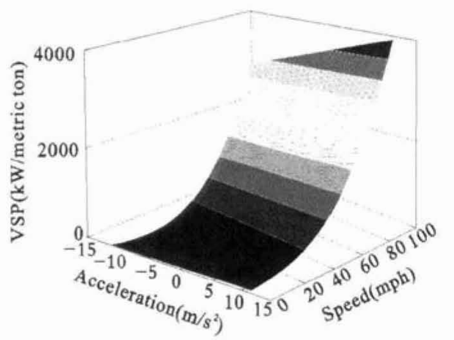


Fig. 1 3D surface of VSP versus acceleration and speed for light duty vehicles

To test the uncertainty and the sensitivity of the VSP equation for light duty vehicles, a Bayesian Monte Carlo sensitivity analysis is performed as described by Saltelli (2002) and Morris et al. (2008). A Latin Hypercube (LH) sampling based method for estimation of the "Sobal" sensitivity indices is described as follows:

1st order for input i

$$S(i) = \frac{Var(E[f|x_i|])}{Var(f)} \quad (6)$$

where x_i is the ith input.

Total effect for input i

$$T(i) = \frac{E[Var(f|x_{-i}|)]}{Var(f)} \quad (7)$$

where x_{-i} is all inputs except ith.

The probability distribution on the inputs with respect to which sensitivity is being investigated by investigates the moments with respect to the appropriate marginal of the uncertainty distribution. By approach, the integrals involved are approximated through averages over properly chosen samples based on two LH samples proportional to U. The sensitivity analysis is performed in R with the fully Bayesian Monte Carlo sensitivity analysis scheme. Random Latin hypercube samples are drawn at each Markov Chain Monte Carlo (MCMC) iteration in order to estimate main effects as well as 1st order and total sensitivity indices. The quality of sensitivity analysis is dependent on the size of the LH samples used for integral approximation; as with any Monte Carlo integration scheme, the sample size must increase with the dimensionality of the problem. The total sensitivity indices T are forced non-negative, and if negative values occur it is necessary to increase the sample size.

Figure 2 shows the main effects, first order sensitivity indices and the total effect sensitivity indices of the VSP for light duty vehicles. The main effects figure shows that both speed and acceleration have is more sensitive to the VSP. However, the speed largest response on the VSP since it has a sharper slope comparing to the acceleration slope. Grade, unlike the speed and acceleration, has less impact on that VSP since it has low response on the main effects. The first order and total effect indices conformed that the speed has the more impact on the VSP of light duty vehicles while acceleration and grade have less impact.

The main effects with the mean and 90 percent interval plot show the amount of uncertainty from the results of the given MCMC iteration. Fig. 3 shows the range of the 90 percent interval range and the mean of the main effects of speed, grade and acceleration. It is consistent with Fig. 2 that the speed has more impact but less uncertainty. However, the grade and acceleration have less impact but more uncertainty on the VSP for light duty vehicles.

4.2 STP sensitivity analysis for heavy duty vehicles

Results from sensitivity tests on the STP for heavy duty vehicles were also reported below. However, since the STP parameters for each MOVES regulatory class (LHD, MHD, HHD and BUS) for heavy duty vehicles are available, the LH sampling based method for estimation of the "Sobal" sensitivity indices are presented. Since the STP parameters do not contain the roadway grade, only the effects and uncertainties of speed and acceleration rate are presented. Fig. 4 shows the main effects, first order and total effect sensitivity indices for LHD, MHD, HHD and BUS.

Similar to the VSP sensitivity results, the speed has significant impact on the response for main effects while acceleration's response is much smaller. As a result, speed has high first order and total effect sensitivity indices compared to the acceleration. Very similar sensitivity response and indices values are observed for each MOVES regulatory class: LHD, MHD, HHD and BUS.

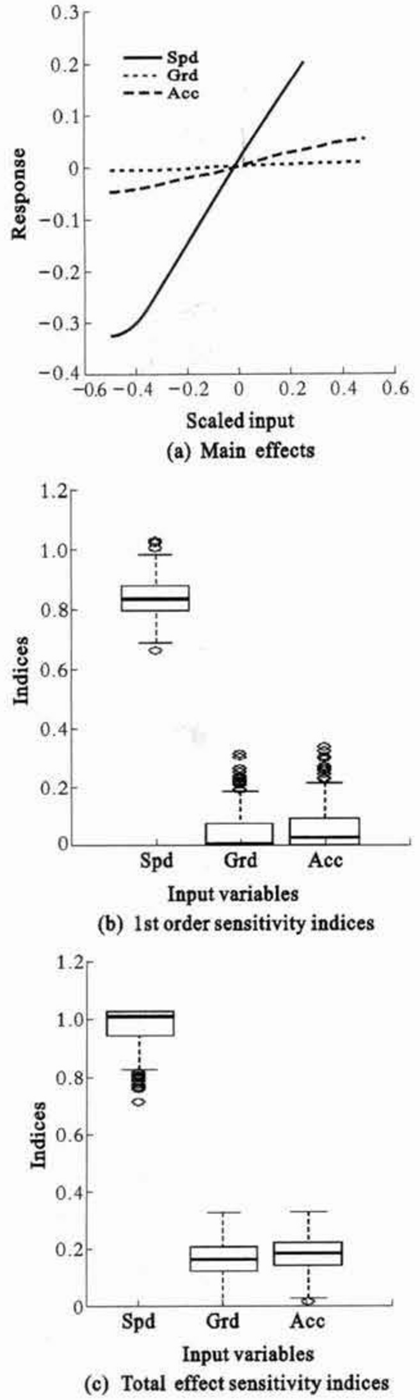


Fig. 2 Sensitivity results for VSP on speed (Spd), grade (Grd) and acceleration (Acc)

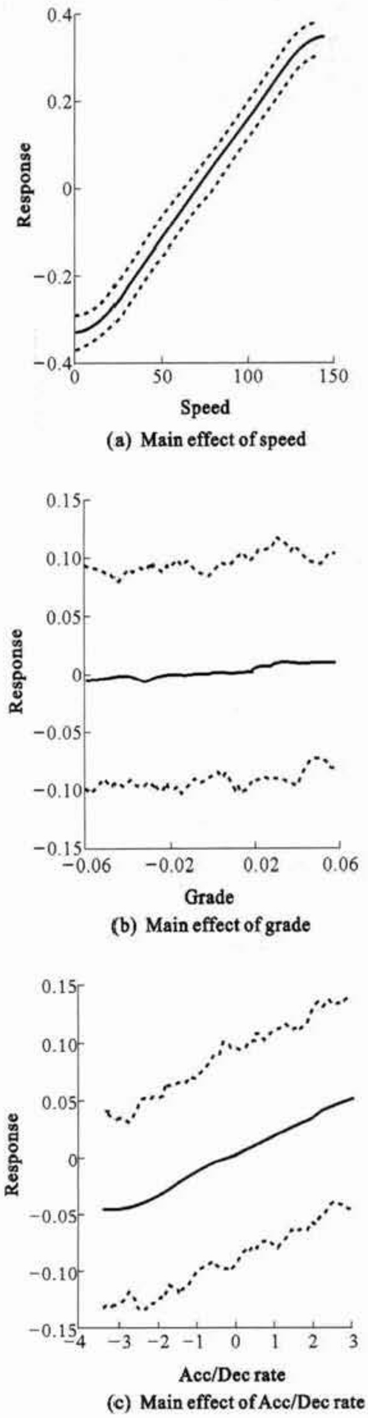


Fig. 3 Main effects of speed, grade and acceleration on VSP

Figure 5 shows the main effects with the mean and 90 percent interval. It suggests the same observation with the VSP for light duty vehicles. Speed has more impact with fewer uncertainties while acceleration has less impact on the response but presents more uncertainty since its 90 percent interval curves tend to cover larger area. Similar results were found for all heavy duty vehicle STP sensitivity test results.

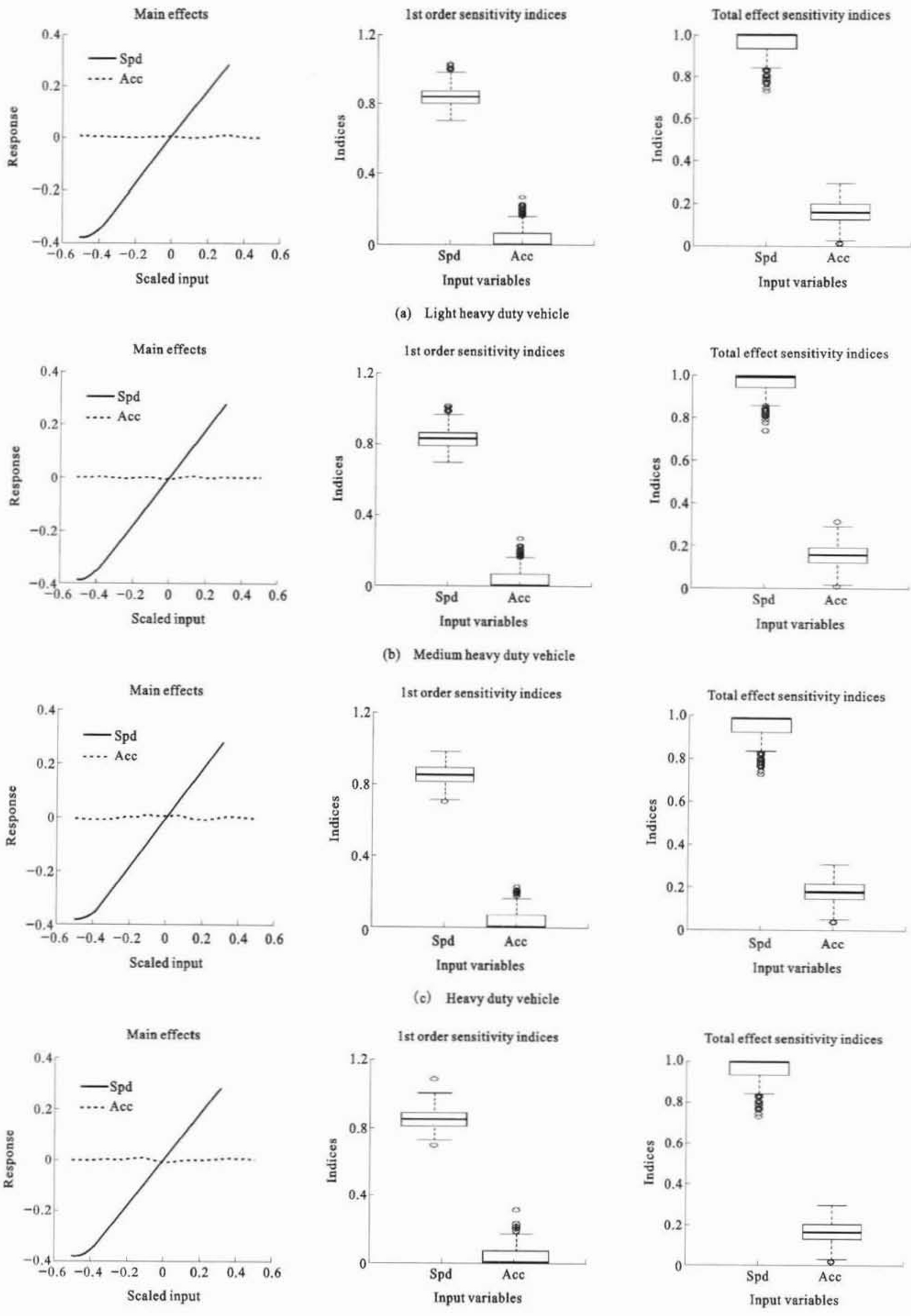
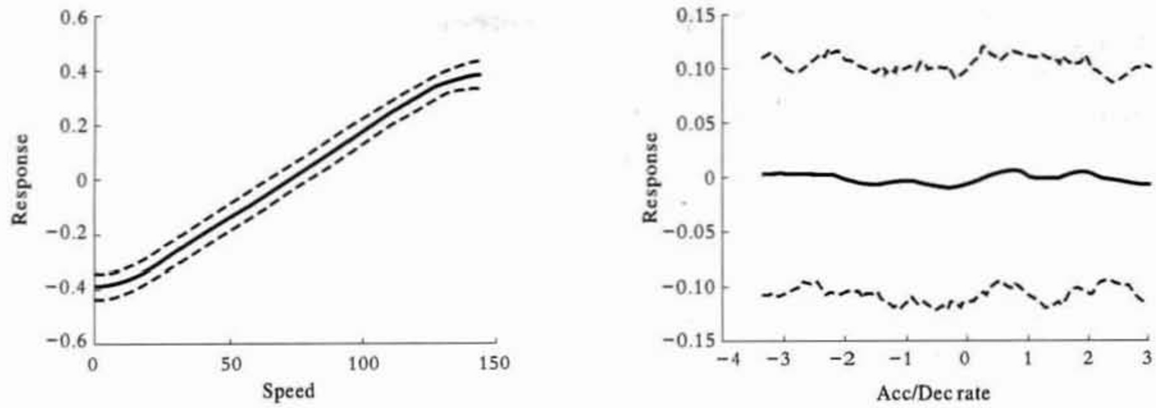
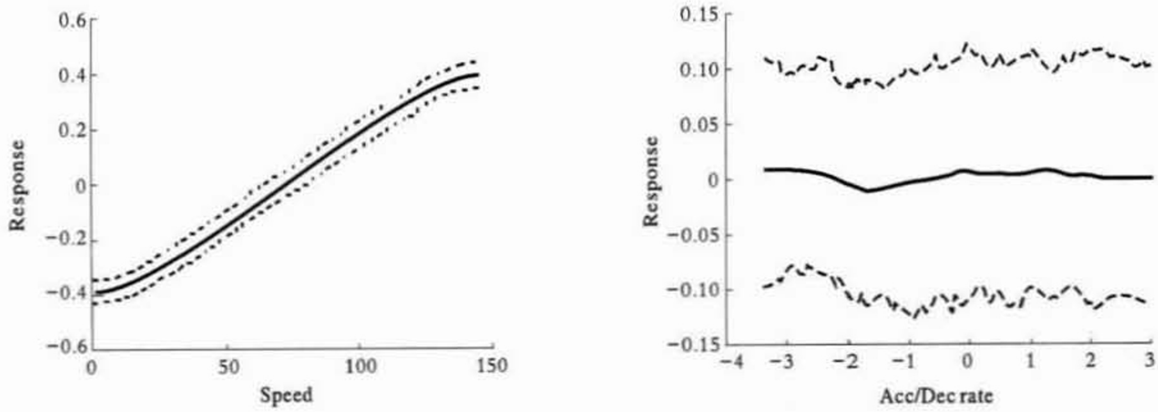


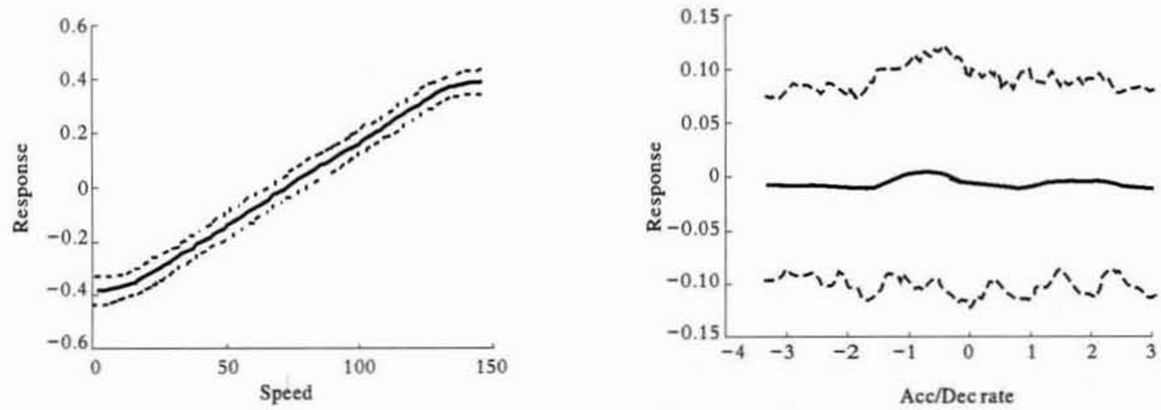
Fig. 4 Main effects, first order sensitivity indices and total effect sensitivity indices for LHD, MHD, HHD and BUS



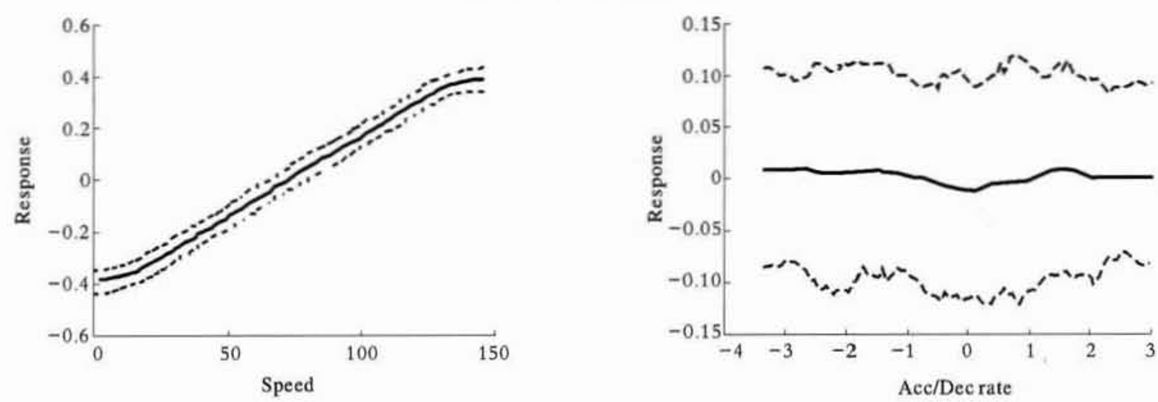
(a) Light heavy duty vehicle



(b) Medium heavy duty vehicle



(c) Heavy heavy duty vehicle



(d) Urban bus

Fig. 5 Main effects with mean and 90 percent interval

4.3 MOVES emission rates sensitivity results

Since the sensitivity tests on the VSP and STP results showed that the speed is the most critical factor among the traffic activity variables, it is important to show how MOVES model emission responses to the vehicle operational speed.

To test the MOVES model sensitivity of speed, a series of MOVES run with hypothetical traffic activity data inputs was performed. The MOVES model was set to year 2013, August from 07:00 to 07:59 AM. The MOVES geographic bounds were set to Hamilton County, Ohio. Road type was set to urban restricted access to simulate the running emissions on interstate freeways. Pollutants modeled include: HC, CO, NO_x, VOC, energy consumption (Energy) and primary exhaust PM2.5 (PM2.5). Other project level emission analysis data including vehicle age distribution, fuel supply and formulation, and meteorological data were set to default.

Figure 6 shows the emission rates versus traffic speed. All curves showed higher emission rates at lower speed ranging from 0 to 20 mph. This shows agreement with literatures stating lower speeds corresponding to higher emissions. Generally, as speed increases to the range of 25 to 60 mph, the emission rates tend to be lower with NO_x as an exception of increasing. However, when the speed reaches the range of 70 to 85 mph, almost all pollutants showed an increasing trend. This is a consistent with the literatures where when vehicle operational speed reaches a higher speed (75 mph), the emissions tend to increase. Pollutant type wise, NO_x showed a little different curve from the rest. The minimum NO_x emission rates are at 25 mph range and maximum while running above 25 mph is approximately at 75 mph range. One can also see from Fig. 6 that in order to obtain an lowest vehicle running emission, it is best to operate traffic flow at the 50 mph range.

Figures 7-10 show the MOVES emission rates for heavy duty vehicles. The emission curves at different speed range showed a monotonic trend that when the speed goes higher, the emission rates would reduce. Significant decrease of emission rate occurs at the speed range of 0 and 25 mph. The magnitude of difference can be up to four times larger for almost all of the pollutants. CO emissions for light heavy duty vehicles exhibited a small trend of increasing at the speed of 75 mph. Otherwise, no significant differences were identified for the emission rates versus speed among light heavy duty, medium heavy duty, heavy heavy duty and urban bus classes.

5 Conclusions

Sensitivity analysis is used to determine how "sensitive" a model is to changes in the model parameter values. Sensitivity analysis helps to build confidence in the model by studying the uncertainties that are often associated with parameters in models The MOVES project level sensitivity analysis is performed based on a Latin Hypercube sampling for estimation of the "Sobal" sensitivity indices for its key concepts: VSP and STP. Sensitivity tests of emission rates to vehicle operating speed was performed as well.

MOVES sensitivity analysis helps the modelers to understand the dynamics of the model system and allows modelers to determine what level of accuracy is necessary for a parameter to make the model sufficiently useful and valid. For vehicle specific power, the tests reveal that the MOVES model is very sensitive to vehicle operating speed, and then it may be possible to use a value with greater precision rather than an estimate. The tests also identified that the acceleration and grade as critical factors but the magnitude of significance indicated by its first order and total effect sensitivity indices is much less than that of vehicle speed. As of the scaled tractive power, similar results on the heavy duty vehicles are identified. MOVES emission rate versus operating speed curves showed that at lower speed range (below 25 mph), the emission rates can be four times higher than the higher speed range (higher than 25 mph, lower than 75 mph). However, for most of the modeled pollutants, the emission rates tend to increase while vehicle operating speed is greater than 75 mph.

Although this study focused on the sensitivity test of VSP/STP and MOVES project level emission rates, the simulation on the VSP/STP binning has not been studied. MOVES project level sensitivity analysis of the specific VSP/STP variables including the grade and acceleration should be further studied.

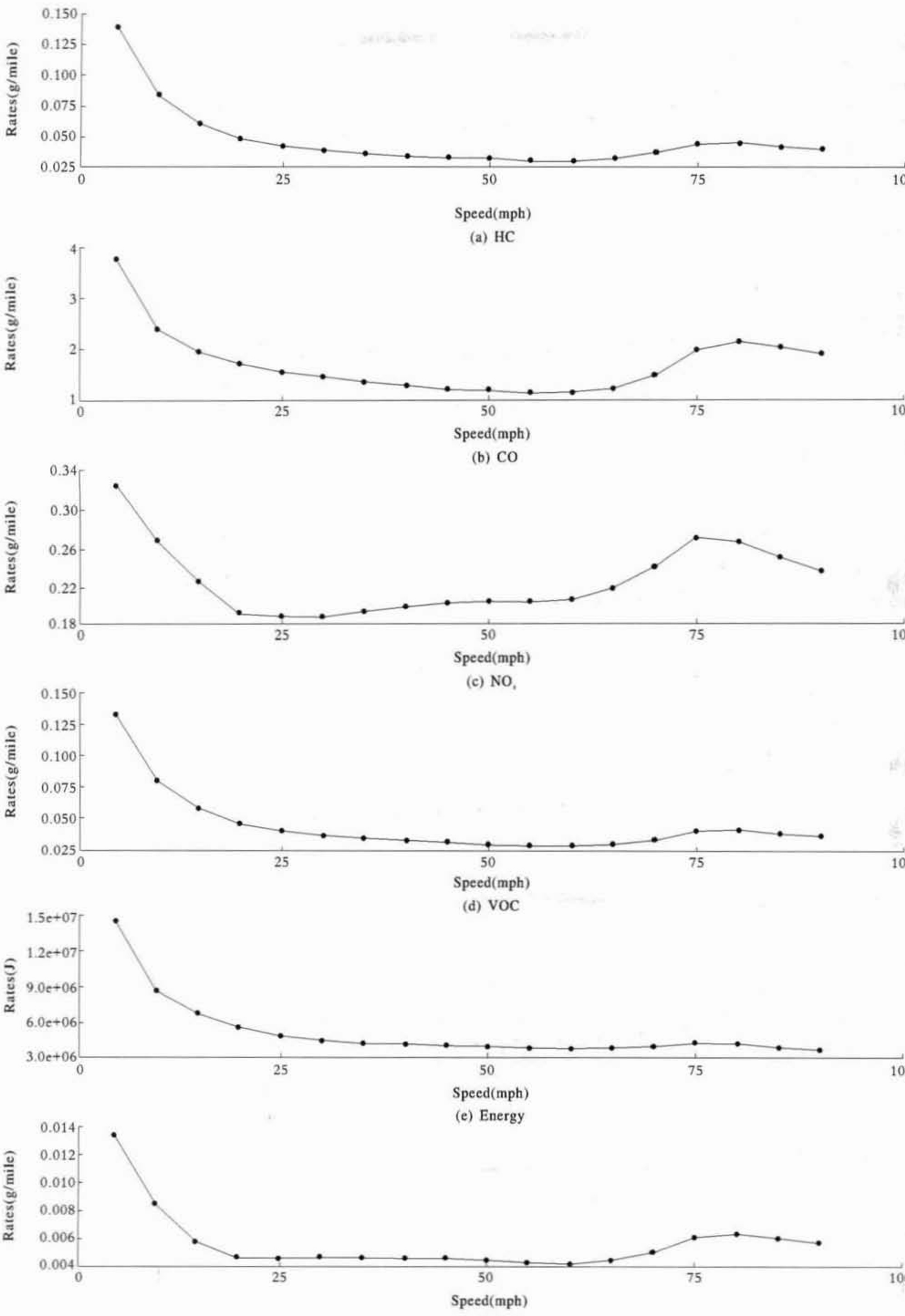
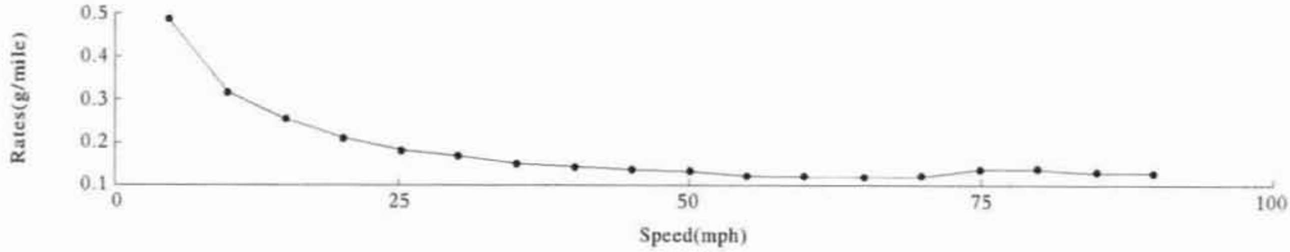
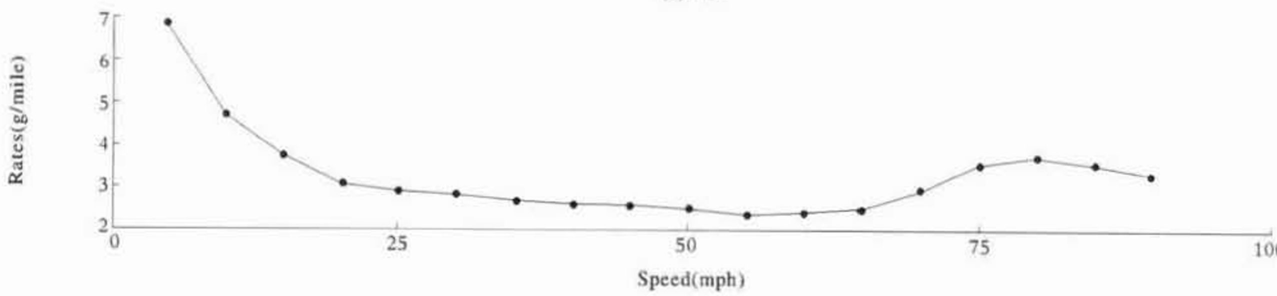


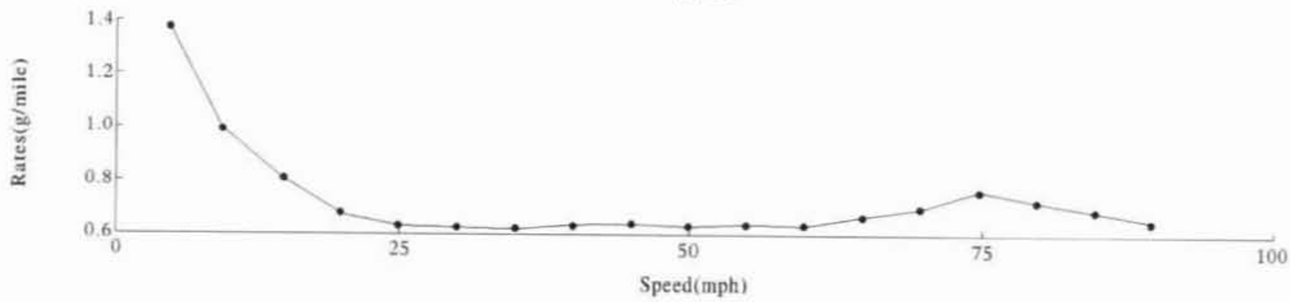
Fig. 6 MOVES emission rates versus speed for light duty vehicles



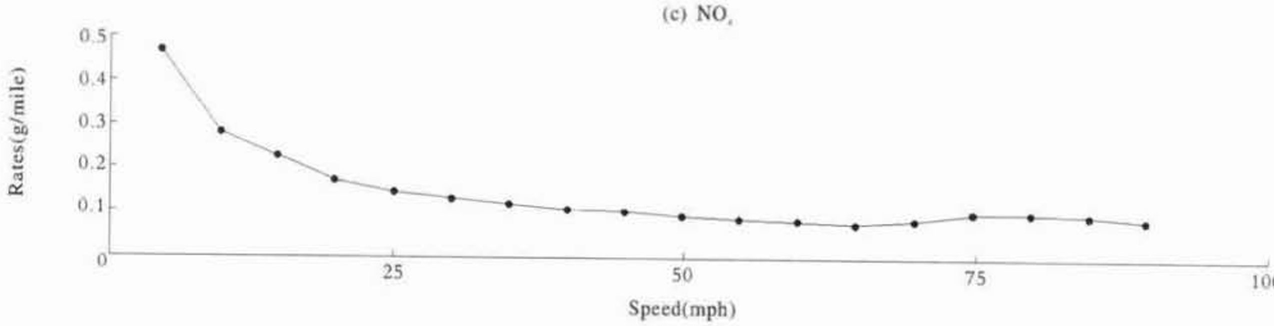
(a) HC



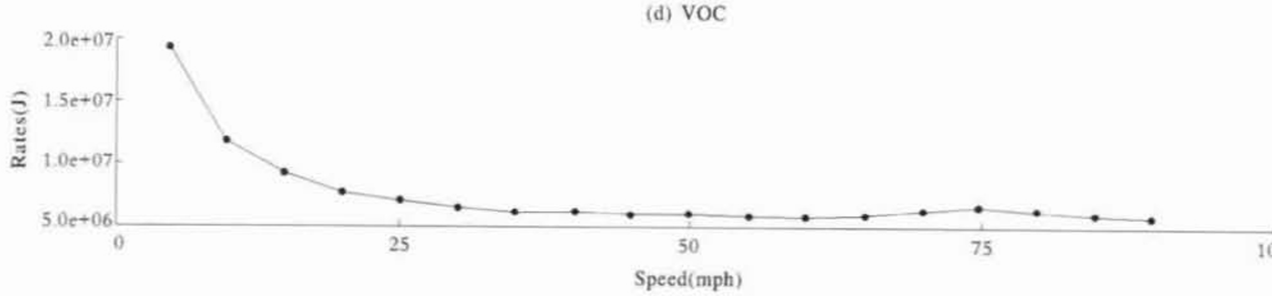
(b) CO



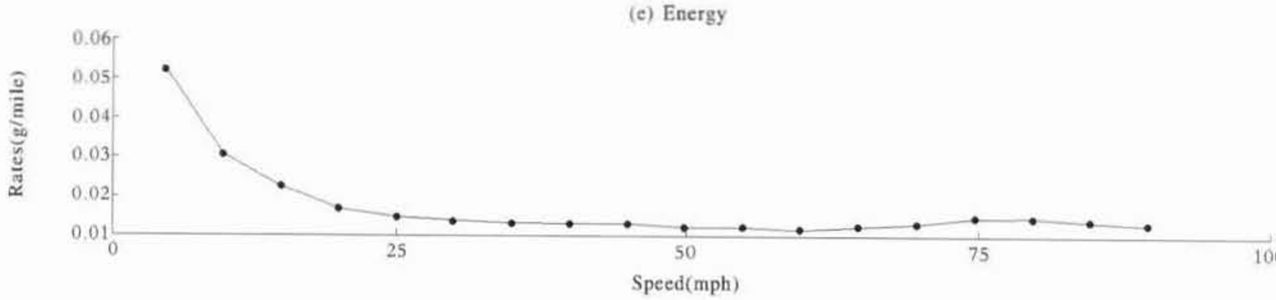
(c) NO_x



(d) VOC



(e) Energy



(f) PM2.5

Fig. 7 MOVES emission rates versus speed for LHD vehicle

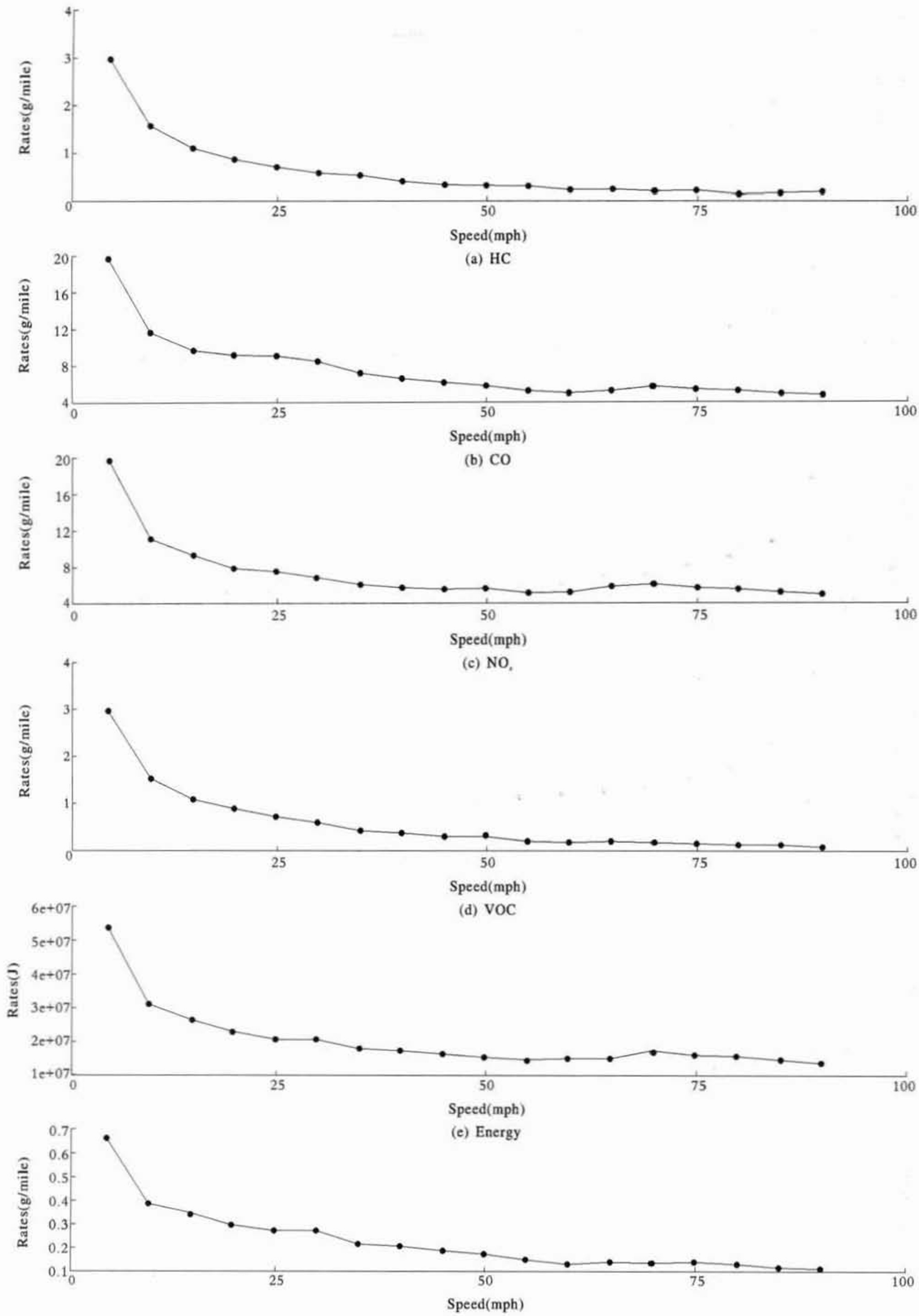


Fig. 8 MOVES emission rates versus speed for MHD vehicle

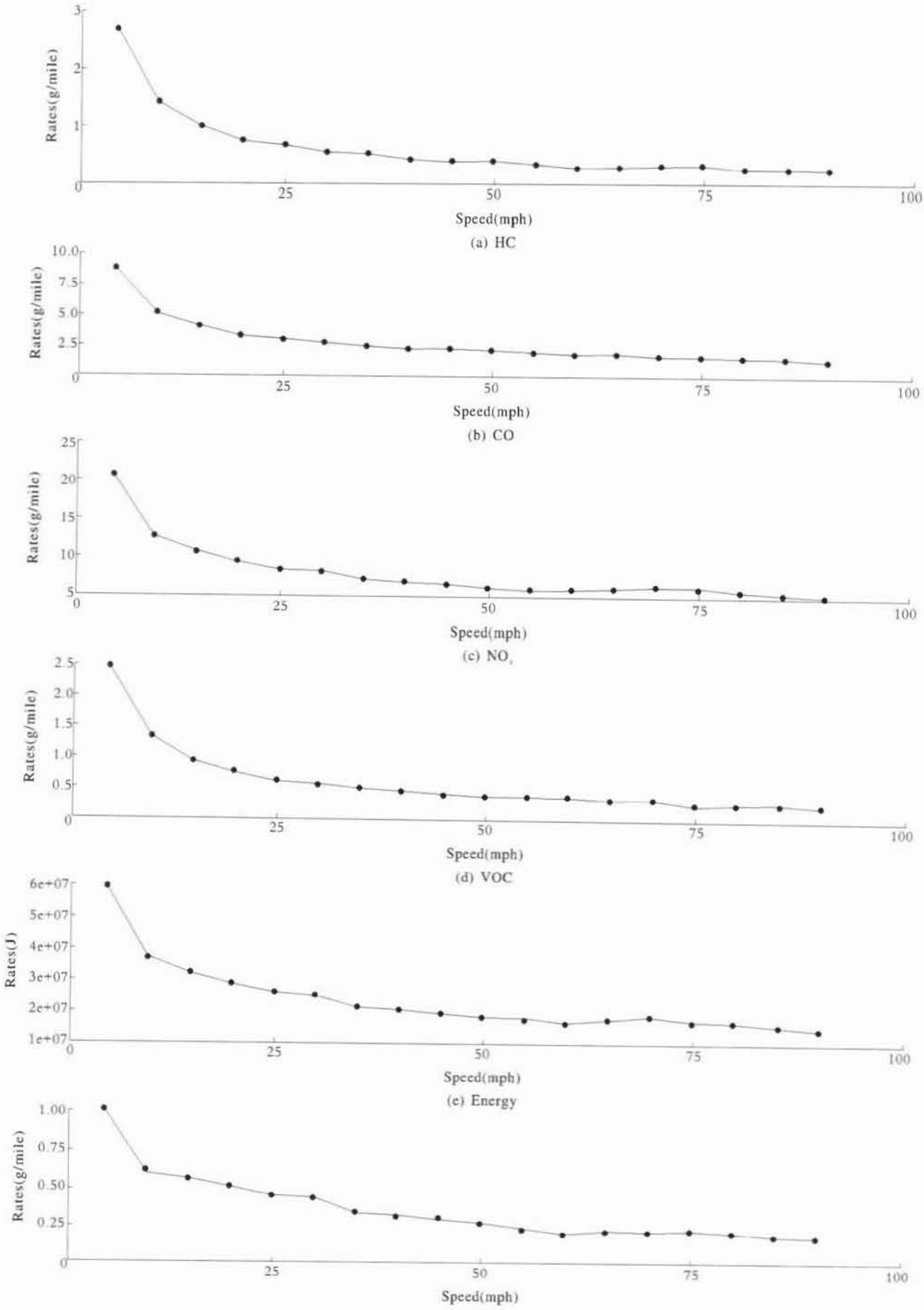


Fig. 9 MOVES emission rates versus speed for HHD vehicle

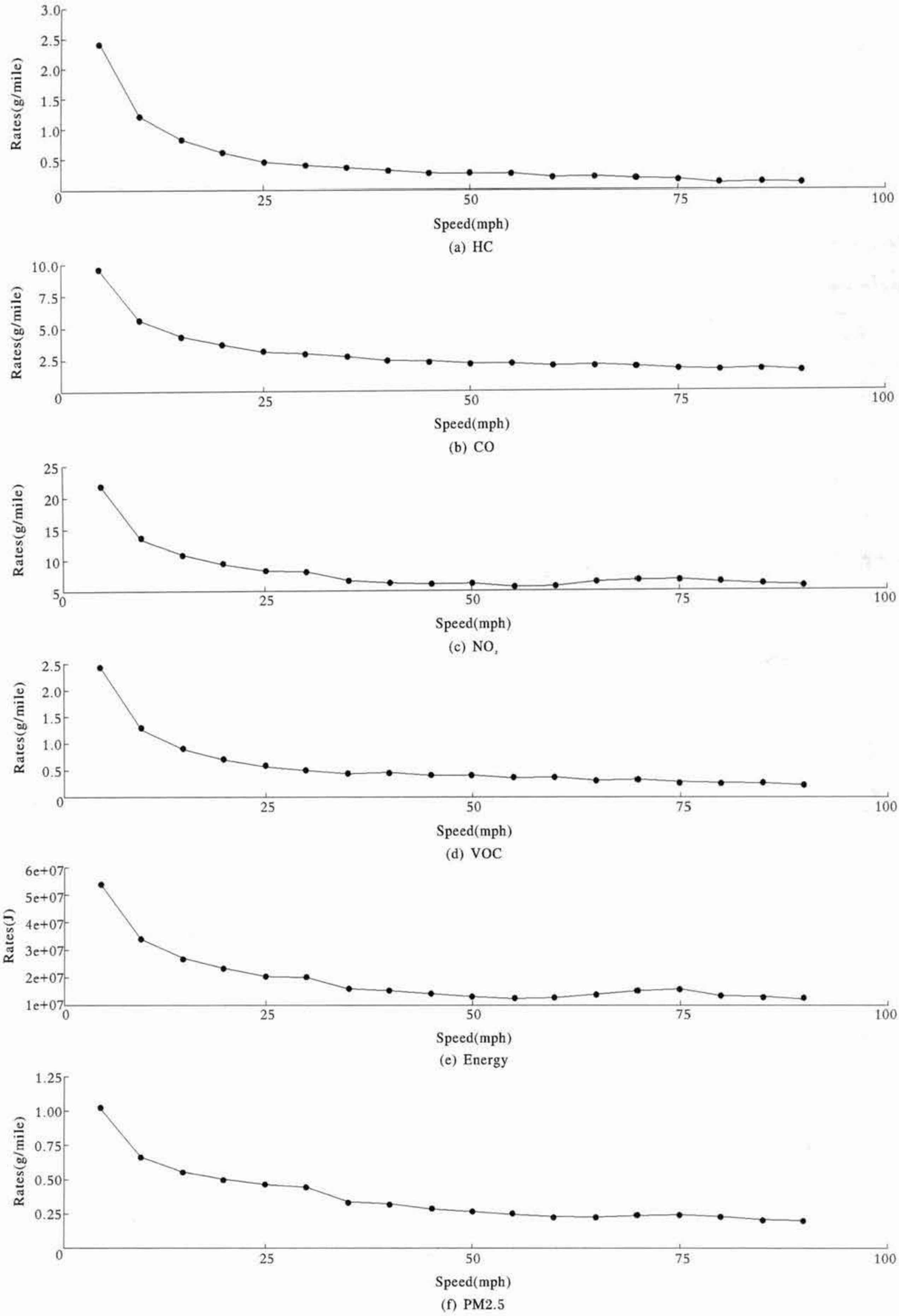


Fig. 10 MOVES emission rates versus speed for urban bus

Acknowledgments

The authors are appreciative for the support by U. S. Environmental Protection Agency and Ohio Department of Transportation. Any opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the agency.

References

Boriboonsomsin, K., Barth, M., 2009. Impacts of road grade on fuel consumption and carbon dioxide emissions evidenced by use of advanced navigation systems. Transportation Research Record, 2139: 21-30.

Fambro, D. B., Koppa, R., Fitzpatrick, K., 1997. Determination of stopping sight distances. NCHRP report 400, National Cooperative Highway Research Program, Transportation Research Board, Washington DC.

Fancher, P. S., Gillespie, T. D., 1997. Truck operating characteristics. NCHRP Synthesis of Highway Practice, Transportation Research Board of the National Academies, Washington DC.

Fernũndez, P. C., Long, J. R., 1995. Grades and other loads effects on on-road emissions: an on-board analyzer study. Proc., Fifth CRC On-Road Vehicle Emission Workshop, San Diego, Calif.

FHWA, 1998. Development and testing of INTRAS: a microscopic freeway simulation model-Vol. 1-3. Report FHWA/RD-80/106-108, Federal Highway Administration, US-DOT, McLean, Virginia.

FRESIM User Guide, 1994. Technical report Version 4.5. Federal Highway Administration, US-DOT, McLean, Virginia.

Gates, T. J., Noyce, D. A., Laracuente, L., 2007. Analysis of dilemma zone driver behavior at signalized intersections. Compendium of Papers CD-ROM, 86th Transportation Research Board Annual Meeting, Washington DC.

Gong, H., Chen, C., Bialostozky, E. M., et al., 2012. GPS/GIS method for travel mode detection in New York City. Computers, Environment and Urban Systems, 36(2): 131-139.

Hallmark, S. L., Guensler, R., Fomunung, I., 2002. Characterizing on-road variables that affect passenger vehicle modal operation. Transportation Research Part D, 7: 81-98.

Harwood, D. W., Torbic, D. J., Richard, K. R., et al., 2003. Truck characteristics as factors in roadway design. NCHRP Report 505, Transportation Research Board of the National Academies, Washington DC.

Houk, J., 2009. FHWA MOVES sensitivity testing. Midwest Transportation Air Quality Summit.

Jiménez-Palacios, J., 1999. Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing. PhD thesis, Massachusetts Institute of Technology, Cambridge, Mass.

Morris, R. D., Kottas, A., Taddy, M., et al., 2008. A statistical framework for the sensitivity analysis of radiative transfer models. IEEE Transactions on Geoscience and Remote Sensing, 46 (12): 4062-4074.

Movable Type Scripts, 2012. Calculate distance, bearing and more between latitude/longitude points. http://www.movable-type.co.uk/scripts/latlong.html.

Nam, E. K., 2003. Proof of concept investigation for the physical emission rate estimator (PERE) to be used in MOVES. EPA420-R-03-005, USEPA Office of Transportation and Air Quality, Assessment and Standards Division, Ann Arbor, MI.

Nam, E. K., Robert, G., 2005. Fuel consumption modeling of conventional and advanced technology vehicles in the physical emission rate estimator (PERE). EPA420-P-05-001, U. S. EPA Office of Transportation and Air Quality, Assessment and Standards Division, Ann Arbor, MI.

Noel, G. J., 2013. MOVES regional level sensitivity analysis. Transportation Research Board Annual Meeting, Regional Transportation Air Quality Subcommittee, Washington DC.

Noel, G. J., Wayson, R., 2012. MOVES2010a regional level sensitivity analysis. DOT-VNTSC-FHWA-12-05, U. S.

Park, S., Rakha, H., 2005. Energy and environmental impacts of roadway grades. Compendium of Papers CD-ROM, 84th Transportation Research Board Annual Meeting, Washington DC.

Pline, J. L., 1999. Traffic engineering handbook. Prentice Hall, Englewood Cliffs, New Jersey.

Qstarz BT-Q1000EX Specifications, Qstarz International Co., Ltd., 2012. http://www.qstarz.com/Products/GPS%20Products/BT-Q1000EXQR-S.htm.

Saltelli, A., 2002. Making best use of model evaluations to compute sensitivity indices. Computer Physics Communications, 145 (2): 280-297.

U. S. EPA, 2011. Development of emission rates for light-duty vehicles in the motor vehicle emissions simulator (MOVES2010). EPA-420-R-11-011, U. S. Environmental Protection Agency.

U. S. EPA, 2012a. Policy guidance on the use of MOVES2010 and subsequent minor revisions for state implementation plan development, transportation conformity, and other purposes. EPA-420-B-12-010, Office of Transportation and Air Quality, U. S. Environmental Proteetion Agency.

U. S. EPA, 2012b. Development of emission rates for heavy-duty vehicles in the motor vehicle emissions simulator MOVES2010. EPA-420-B-12-049, Office of Transportation and Air Quality, U. S. Environmental Protection Agency.

U. S. EPA, 2013. MOVES(motor vehicle emission simulator) modeling and inventories. http://www.epa.gov/otaq/models/moves/index.htm.

Vallamsundar, S., Lin, J., 2013. Sensitivity test analysis of MOVES and AERMOD models. Compendium of Papers CD-ROM, 92nd Transportation Research Board Annual Meeting, Washington DC.

Yang, Q., 1992. Simulation laboratory for evaluation of dynamic traffic management systems. Thesis, Presented to Gillespie, T., Fundamentals of Vehicle Dynamics, Society of Automotive Engineers, Warrendale, Pa.

Zhang, K., Frey, H.C., 2005. Road grade estimation for on-road vehicle emissions modeling using LIDAR data. Proceedings, Annual Meeting of the Air & Waste Management Association, Minneapolis, MN.