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Methodology for Developing Transit Bus Speed–Acceleration Matrices for Load-Based Mobile Source Emissions Models

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An emissions model for transit bus based on road load estimates emissions as a function of transit bus power demand for given transit bus activities and environmental conditions. Transit bus speed and acceleration rates are key activity parameters and are the most important parameters in the estimation of transit bus power demand, also known as engine load. Once the transit bus engine load is calculated for a given speed and acceleration, emissions in grams per vehicle hour can be calculated with grams per brake-horsepower hour emission rates. However, collecting speed and acceleration data on various road types and times of day requires extensive efforts for use in load-based mobile source emissions models. To quantify Atlanta regional transit bus speed and acceleration rates, the Georgia Institute of Technology research team installed trip data in a transit bus operated by the Metropolitan Atlanta Rapid Transit Authority. The team collected second-by-second speed and location data for 3 weeks on a variety of routes and created speed–acceleration matrices by roadway facility type and time of day. This paper focuses on developing a methodology to create transit bus speed–acceleration matrices for use in load-based modal emissions models for the Atlanta metropolitan area. Once a bus service route is specified by roadway facility type and time of day, engine power demand for each speed–acceleration matrix bin can be calculated, weighted by activity frequency on each corresponding matrix bin, and then multiplied by baseline emissions rates that can be obtained from engine dynamometer or chassis dynamometer test results.

Since 2000, the U.S. Environmental Protection Agency has been developing a new generation mobile source emissions model (motor vehicle emission simulator, MOVES) based on vehicles' specific power requirements. Vehicle-specific power (VSP) is a function of speed, acceleration, and road grade (*1*). In general, a vehicle with higher speed, harder acceleration, and steeper road grade requires more VSP to overcome resistance and drag forces. However, collecting speed and acceleration data on various roads during different time periods and simulating emissions for the development of emissions inventories and the microscale air-quality assessment requires extensive effort and resources.

The Georgia Institute of Technology (Georgia Tech) research team obtained second-by-second speed and location data using the Georgia Tech Trip Data Collector equipped with a Global Positioning System (GPS) receiver. With second-by-second data, the research team developed transit bus speed–acceleration matrices, which were designed for use in load-based modal mobile source emissions models. As an emerging vehicle speed data collection tool in the transportation research filed, GPS receivers provide speed data calculated based on Doppler shift theory (*2*). In studies of vehicle speed accuracy using GPS receivers, vehicle speed from GPS receivers is as accurate as speed obtained from conventional distance measuring instruments (*3*) or travel time data acquisition systems (*4*). When data collected from the vehicle speed sensor (VSS) are compared with GPS speed for speeds less than 5 miles per hour (mph), significant percentage speed differences are noted (*5*). Because each data stream is subject to different error sources, research efforts are ongoing to quantify the impacts of low-speed errors on load prediction. Speed and acceleration at low speeds are important in the load-based calculations for drivetrain inertia, so it is important to ensure that low-speed errors are random and do not introduce bias. Nevertheless, for the purposes of the analyses presented here, the impacts of any such differences should be minor.

For this research, the Georgia Tech research team installed a trip data collector on a transit bus operated by Metropolitan Atlanta Rapid Transit Authority (MARTA) and collected second-by-second speed data for 3 weeks (June 28 to July 17, 2004). Transit bus speed and location data were collected by GPS, stored on the system, and remotely transmitted to a Georgia Tech data server. From second-by-second speed data, researchers calculate corresponding second-by-second acceleration. Then, speed and acceleration data are grouped by roadway facility type and time of day and used to create speed–acceleration matrices, which can be applied as inputs in load-based modal mobile source emissions models. With activity frequency binned in speed–acceleration matrices, engine power demand can be estimated for each matrix cell. For the estimation of emissions in grams per hour (g/h), estimated engine power demand for each speed–acceleration cell is multiplied by each year's emis-

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sions level in grams per brake-horsepower-hour (bhp-h), which can be obtained from engine or chassis dynamometer test results.

METHODOLOGY

Researchers monitored speed and location data of a bus for 3 weeks, as the bus operated on more than 11 MARTA bus routes. Only speed data along regular bus service routes during weekdays from valid GPS operation were selected for the generation of speed–acceleration matrices by roadway facility type and by time of day. Through a geographic information system (GIS) map-matching process, roadway facility types (arterials and local roads), on which speed data were collected by the trip data collector, were identified. Through the map-matching process, four types of transit bus activities were observed: regular bus service on service routes, approach for service, return after service, and idle at garages. Among the four types of services, only the regular bus service activity was considered for the speed and acceleration analyses because the characteristics of the other activities were generically different from the regular bus service activity (longer idle time, less frequent stops, etc.). During the 3-week study period, the bus served 11 regular bus routes for more than 15 vehicle-days in total (Figure 1). Then, speed data for each roadway facility type were grouped by four time periods defined by the Atlanta Regional Commission for regional transportation planning purposes (*6*). The time periods are morning (6 to 10 a.m.), midday (10 a.m. to 3 p.m.), afternoon (3 to 7 p.m.), and night (7 p.m. to 6 a.m.).

GPS Antenna Installation

Because satellite signals can be blocked by tall buildings and overcasting trees, the GPS antenna was installed on the top of the transit bus roof (Figure 2). It allowed the GPS antenna to receive signals from as many satellites as possible. To obtain reliable GPS data, it is recommended that a GPS receiver receive a minimum of four satellite signals at the same time (*7, 8*). In addition, the position dilution of precision (PDOP) value, which is the measure of current satellite geometry, can be used to evaluate reliable GPS data. A lower PDOP value indicates a more accurate GPS position to receive satellite signals.

Speed Data Collection and Transmission

The Georgia Tech trip data collector consists of four main components: a 386-Linux computer with data storage, a GPS receiver, a wireless communication device, and an onboard diagnostic (OBD) data communication device for light-duty vehicles (*9*). In this study, the light-duty OBD data communication device was disabled because the communication protocol is not the same as that used by the transit bus OBD system. When the transit bus engine is started, the trip data collector begins collecting second-by-second speed and location data. Through the wireless communication device, speed and location data are remotely transmitted to a server computer managed by the DRIVE laboratory in the School of Civil and Environmental Engineering at Georgia Tech.

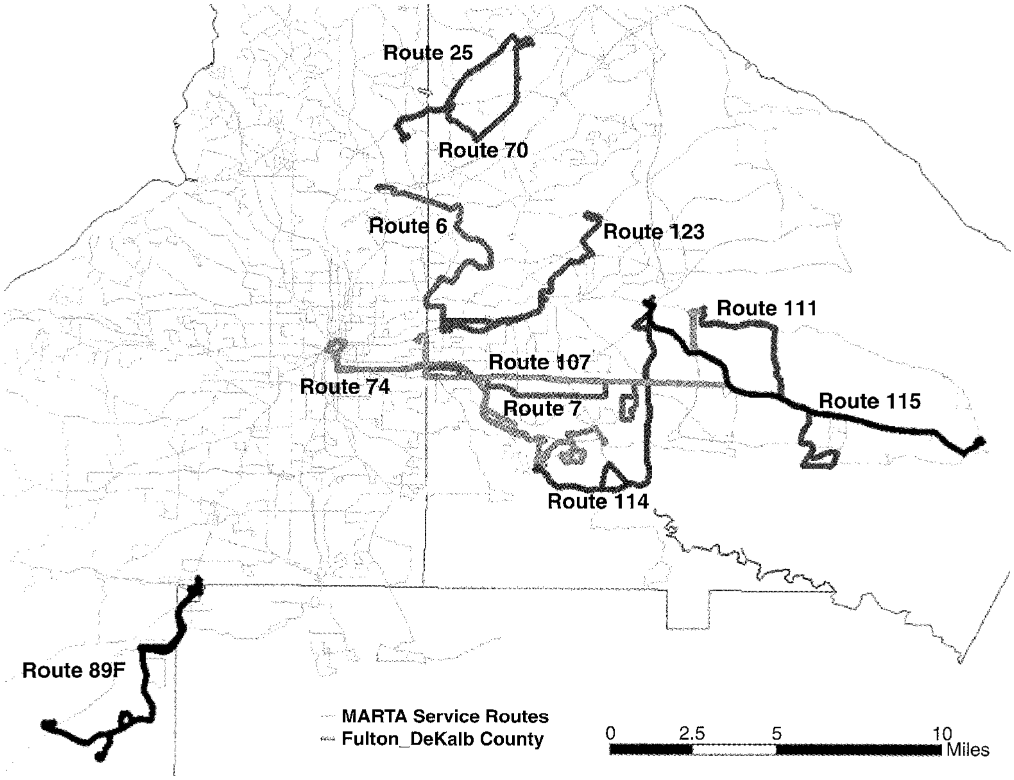


FIGURE 1 Speed and location data collected on MARTA transit bus routes.

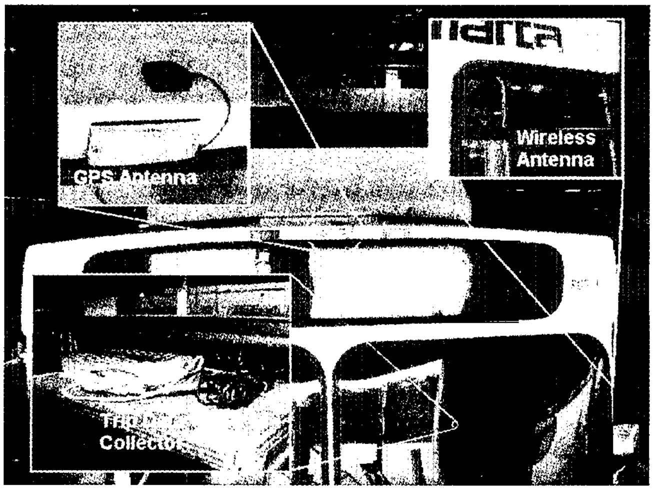


FIGURE 2 Georgia Tech trip data collector installation on a transit bus.

Map-Matching Process

Vehicle position data obtained with the GPS receiver generally do not fall on the center of the GIS digital road links because both the GPS location data and the GIS road links have positional errors from real-world geometric locations. The methodology that places the GPS location data onto the GIS digital road network is called map matching. The map-matching process implemented in this study was based on the shortest path function in ArcInfo (*10*). The digital road map used in this study was the Georgia Department of Transportation Digital Linear Graph road database. This data set provides a 1:2,000,000-scale road layer with a full topological structure. The road functional classes from a road characteristic file were spatially joined to the digital road network based on the road characteristics link identification and mile point information. After the map-matching process, each GPS data point was related to appropriate road segments in the digital road network and associated with the corresponding road characteristics.

Identification of Speed Bins Based on GPS Error

Because vehicle speed data obtained with a GPS receiver are not expected to be as accurate as VSS data, the magnitude of error (GPS speed difference from VSS speed) should be evaluated to identify a valid low-speed bin break point(s). When the magnitude of the differences is widely distributed, the agreement between the two methods is not as great. To evaluate the magnitude of error, speed data, which totaled 908,088 GPS and VSS paired, were used. These paired data were obtained from five passenger vehicles equipped with GPS receivers and VSS devices. The magnitude of error of GPS speed dramatically decreased when more than four satellite channels were received at the same time and when PDOP values were less than six. Therefore, speed data obtained with more than four satellite channels and fewer than six PDOP values were used for evaluation of the magnitude of error and consisted of 790,037 GPS and VSS light-duty vehicle speed data pairs. Speed bins were arbitrarily selected from less than 2.5, 5, 10, 10 to 70, and more than 70 mph; speed bins increased at 10-mph intervals from 10 to 70 mph. For each speed bin, the fraction of the magnitude of error was plotted with the magnitude of difference percentage (Figure 3). For measured speeds less than 5 mph, speed differences were more significant and widely distributed. However, at higher speeds, the magnitude of speed differences significantly decreased; the magnitude of error was less than 20% for more than 77% of the time at a speed greater than 5 mph and less than 5% for more than 94% of time at the speed greater than 20 mph. In this research, therefore, the speed range from 0 to less than 5 mph was selected as the lowest speed bin, and speed bins increased in 5-mph intervals from 5 to 65 mph.

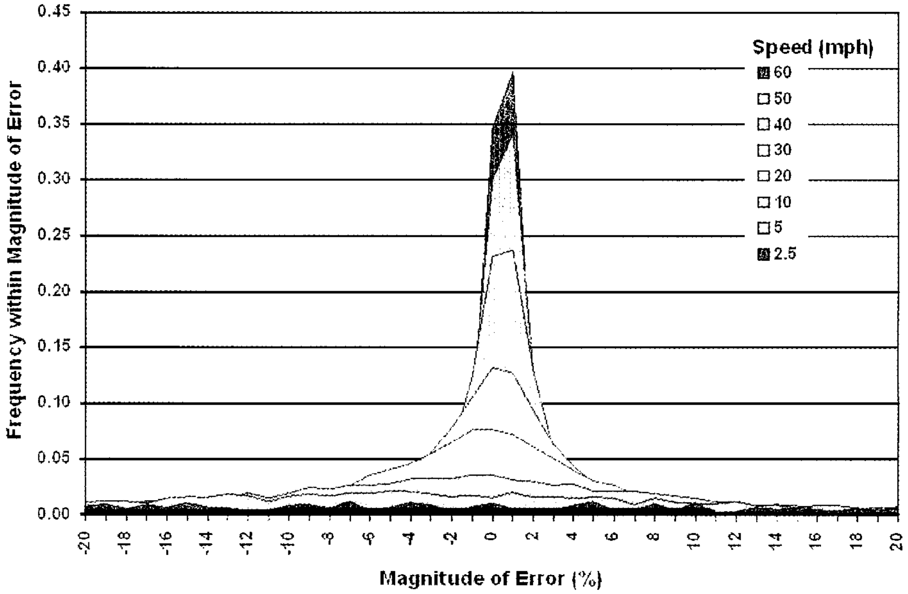


FIGURE 3 Magnitude of GPS speed error ranges and fractions from VSS speed for each speed bin.

Speed Data Processing

To generate speed–acceleration matrices, only speed data on regular bus service routes with valid GPS points during weekdays were selected because the researchers noted that bus activity (speed and acceleration) on the service routes was significantly different from the bus activities leaving or approaching regular service routes or idling at garages.

Because of the data elimination of weak satellite signals (less than five) and high PDOP values (greater than or equal to six) on second-by-second continuous speed data, speed data for analyses became discrete speed data. This may cause inaccurate calculations of acceleration. To avoid the potential errors in acceleration calculation, the first and the last speed and acceleration data in a continuous data block were discarded after acceleration calculation. For better accuracy and for lower error of the acceleration calculation, the researchers used the central difference numerical method (*11*). The central difference numerical method, which adopts two points next to a center point, better reflects the acceleration for the equally time-spaced speed data (*12*).

RESULTS AND DISCUSSIONS

Data points with valid GPS signals on bus service routes provided 229,007 s of activity. Among those data points, 64.6% of the data were obtained on arterials, 34.2% were on local roads, and 1.2% were on freeways. Relatively few data points were observed on freeways, so they were excluded from the analyses. In total, 226,360 data points (148,039 on arterials and 78,321 on local roads) were analyzed to create transit bus speed–acceleration matrices.

Speed and Acceleration Characteristics on Arterials

Speed on arterials ranged from 0 to 65 mph and acceleration ranged from −9 mph/s to +5 mph/s. The speed and acceleration ranges slightly differed by time of day. In the morning, speed ranged from 0 to 50 mph and acceleration ranged from −7 to +3 mph/s. Speed in the other three time periods covered rather wide ranges, from 0 to 65 mph, and acceleration rates ranged from −9 to +5 mph/s by time period from midday to night. Mean bus speeds increased mildly from morning (15.4 mph) to midday (16.0 mph) to afternoon (16.2 mph) time periods. However, the mean speed during the night time period jumped to 19.7 mph. That may be caused by the bus running with lower occupancy in low-volume traffic at night, requiring fewer stops and allowing the bus to run faster than during the other time periods. The research team plans to investigate this bus activity further.

Throughout the day, two high acceleration–deceleration frequency peaks were observed; the first peak was observed at speeds less than 5 mph, and the second peak was observed at a speed range of 20 to 35 mph (Figure 4). At less than 5 mph, the bus acceleration–deceleration frequencies were 32%, 34%, 37%, and 29% of total activity frequency for morning, midday, afternoon, and night time periods. These acceleration–deceleration frequencies ranging from −5 to +3 mph/s occurred because transit buses frequently ran stop and go at bus stops, intersections, and bus terminals. The second high acceleration–deceleration frequencies, ranging from −9 to +3 mph/s, occurred around the speed range of 20 to 35 mph. These second acceleration–deceleration frequencies were equivalent to 35%, 30%, 24%, and 29% of total activity frequency for morning, midday, afternoon, and night time periods.

Speed and Acceleration Characteristics on Local Roads

Speed on local roads ranged from 0 to 45 mph and acceleration ranged from −7 to +5 mph/s. Although occasional high speeds (more than 45 mph) were observed on some local roads, their frequencies were less than 2%. Mean bus speeds slightly decreased from morning (14.4 mph) to midday (13.8 mph) to afternoon (13.2 mph) time periods. However, the mean speed in the night time period jumped to 15.3 mph. The bus ran faster at night than in the other time periods.

As on arterials, two high acceleration–deceleration frequency peaks were also observed on local roads: the first peak at a speed of less than 5 mph and the second peak at the speed range of 15 to 30 mph (Figure 5). Acceleration–deceleration frequencies on both peaks composed most bus activity frequencies: 34%, 37%, 40%, and 28% of total activity frequency at the speed less than 5 mph, and 39%, 34%, 28%, and 38% of total activity at the speed range from 15 to 30 mph for morning, midday, afternoon, and night time periods, respectively.

Speed–Acceleration Matrices and Their Applications

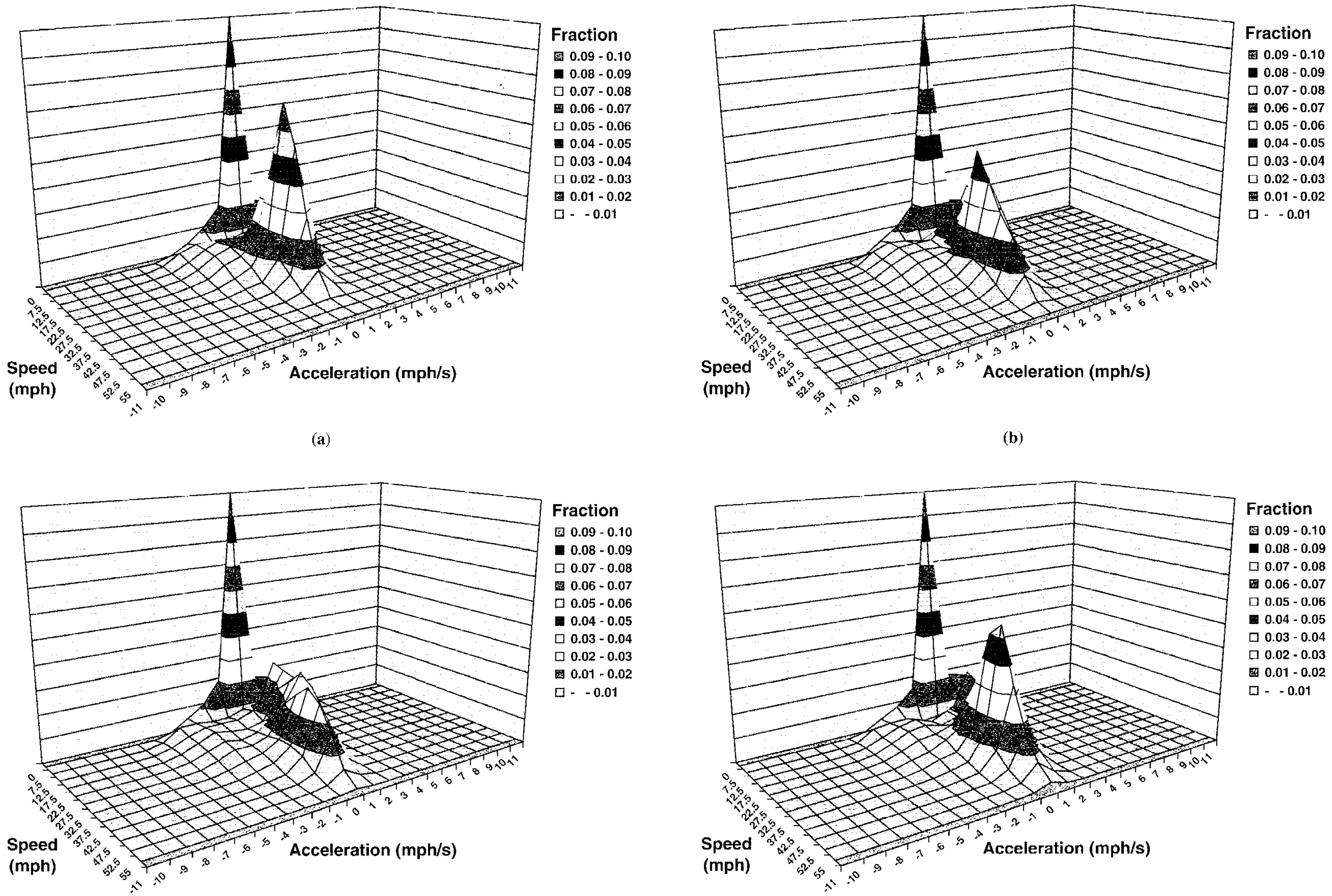
From the speed and acceleration characteristics, the research team created speed–acceleration matrices by roadway facility type and time of day. Speed bins included 0 to 5 mph, 5 to 55 mph in 5-mph increments, and 55+ mph. Acceleration bins included less than −10.5 mph/s, −10.5 to +10.5 mph/s in 1-mph/s increments, and more than +10.5 mph/s. For the zero acceleration bin, acceleration rates ranged from −0.5 to +0.5 mph/s, which helps to compensate for potential GPS receiver error. Cells on speed–acceleration matrices were filled with acceleration–deceleration activity frequencies for corresponding speed and acceleration bins (Figure 6). In Figure 6, bins of each speed and acceleration interval were filled with median values of its interval.

Speeds, accelerations, and activity frequencies in a speed–acceleration matrix can be directly used to estimate transit bus engine power demand and then to estimate emissions in g/h. Once a bus service route is identified by roadway facility type and operation time of day, a proper speed–acceleration matrix can be selected. Engine power demand for each speed–acceleration bin in the speed–acceleration matrix can be estimated with Equation 1.

$$P = \frac{V \cdot \left(\frac{W}{g} \cdot a + F_R + F_W + F_{AD} + F_I \right)}{550} \tag{1}$$

where

P = engine power demand (bhp),
V = vehicle speed (ft/s),
W = vehicle weight (lb),
g = gravitational force (ft/s^2),
a = vehicle acceleration rate (ft/s^2),
F_R = rolling resistance (lbf),
F_W = gravitational drag (lbf),
F_{AD} = aerodynamic drag (lbf),
F_I = inertial resistance (lbf), and
550 = horsepower conversion factor (ft-lbf/s/bhp).



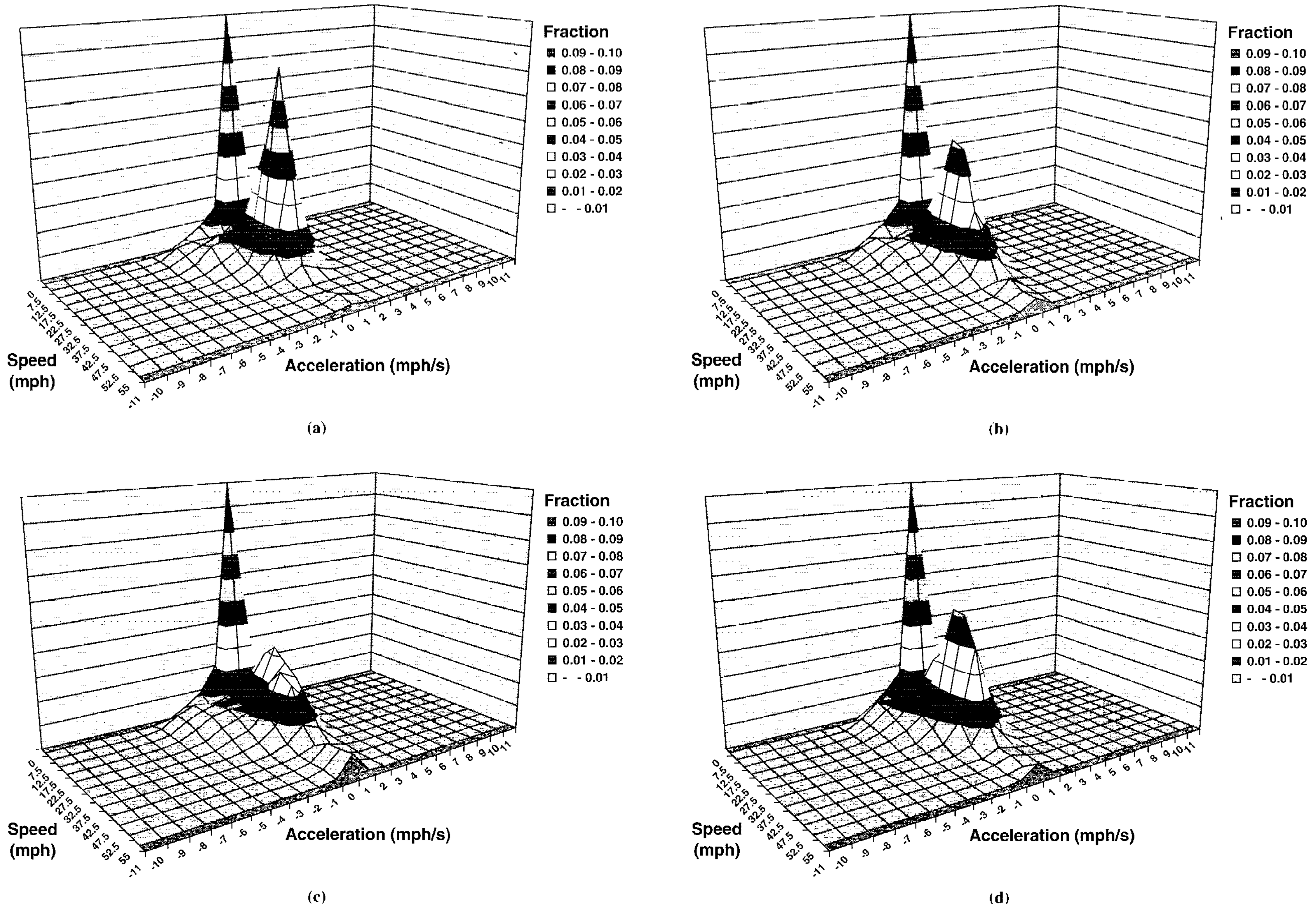
(a)

(b)

(c)

(d)

FIGURE 4 Transit bus arterial speed–acceleration profiles by time of day: (*a*) morning, (*b*) midday, (*c*) afternoon, and (*d*) night.



(a)

(b)

(c)

(d)

FIGURE 5 Local transit bus speed–acceleration profiles by time of day: *(a)* morning, *(b)* midday, *(c)* afternoon, and *(d)* night.

Acceleration (mph/s) Bins	Speed (mph) Bins											
	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	55
-6												
-5		0.001	0.001	0.001	0.001							
-4	0.002	0.005	0.004	0.003	0.002	0.001						
-3	0.005	0.008	0.008	0.008	0.006	0.003	0.002					
-2	0.011	0.007	0.011	0.011	0.008	0.006	0.002	0.001				
-1	0.019	0.006	0.008	0.013	0.015	0.017	0.011	0.006	0.002			
0	0.243	0.008	0.012	0.019	0.045	0.071	0.054	0.028	0.009	0.001		
1	0.024	0.009	0.018	0.030	0.032	0.032	0.019	0.009	0.002			
2	0.019	0.023	0.022	0.020	0.013	0.004	0.001					
3		0.006	0.005	0.002	0.001							
4												
5												
6												

FIGURE 6 Example of a speed–acceleration matrix (arterial, morning).

Engine power demand for each speed–acceleration bin can be weighted by activity frequency in the speed–acceleration bin, and the weighted power demand will be aggregated as a total power demand for the selected roadway facility type and time of day. Then, the total power demand can be multiplied by each bus model year emissions level in g/bhp-h, which can be obtained from engine or chassis dynamometer test results, to estimate emissions for a selected bus service route (Equation 2). Georgia Tech is currently developing a more comprehensive GIS-based, link-level modal modeling approach for heavy-duty vehicles.

$$EM_{i,j} = \sum_k EL_k \cdot \sum_l \sum_m (P_{l,m} \times AF_{l,m})_{i,j} \qquad (2)$$

where

EM = transit bus emissions rate (g/h/vehicle),
EL = transit bus emissions level (g/bhp-h),
P = engine power demand (bhp-h),
AF = acceleration–deceleration activity frequency,
i = roadway facility type (arterial or local road),
j = time of day (morning, midday, afternoon, or night),
k = engine model year,
l = speed in a speed–acceleration matrix, and
m = acceleration in a speed–acceleration matrix.

To demonstrate emissions rate differences at different speeds with Equation 2, two cells (speeds of 7.5 and 37.5 mph at an acceleration of +1 mph/s), which have the same acceleration frequency of 0.009, were selected from Figure 6 (a speed–acceleration matrix for arterials in the morning time period), and transit bus engine power demand was estimated for each speed. Acceleration forces at 7.5 and 37.5 mph were the same because acceleration rates were the same at those speeds. However, the sum of the other forces (rolling resistance, gravitational drag, and aerodynamic drag) at 37.5 mph was 2.2 times greater than at 7.5 mph. This is because aerodynamic and rolling resistance drag forces increase as vehicle speed increases (13). Total engine power demand estimated at 37.5 mph was 5.7 times greater than at 7.5 mph, which implies that transit bus emissions at 37.5 mph will be 5.7 times greater than at 7.5 mph for +1 mph/s acceleration at the condition of linear relationships between emissions level and engine power demand.

CONCLUSIONS AND FUTURE RESEARCH TASKS

Transit bus speed–acceleration matrices are designed to be used in road-load-based transit bus emissions modeling. Speed–acceleration matrices reflecting second-by-second transit bus activity can reflect second-by-second transit bus emissions, which are associated with second-by-second activity. Application of speed–acceleration matrices in the load-based transit bus emissions model can be similarly used in more complex modal activity-based emissions models that can predict emissions in emissions inventory development as well as microscale air-quality assessment.

Because of the small size of speed and location data, this paper presents speed–acceleration matrices only for two aggregated roadway facility types (arterials and local roads) and four aggregated time periods (morning, midday, afternoon, and night time periods).

The methodology to create speed–acceleration matrices will be further refined with other parameters, such as roadway subfacility types, time of day, road grade, vehicle weight, driver behavior, and so forth. With further data collection, speed–acceleration matrices will be incorporated with road grade and vehicle weight, which are also included in engine power demand estimation. With the integration of road grade and vehicle weight, two-dimensional speed–acceleration matrices will become multidimensional speed–acceleration matrices for use in road-load-based modal emissions modeling. In the speed and location data collection, the error range at low bus speed can be improved when obtained with more reliable data collection devices such as the differential GPS or the vehicle speed sensor via an engine connection. In addition, bus driver behavior should be investigated and incorporated into the multidimensional matrices because different bus drivers likely drive the same bus on the same route in a different manner.

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