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Variability of Heavy-Duty Vehicle Operating Mode  
Frequencies for Prediction of Mobile Emissions

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16. ABSTRACT The paper discusses a new geographic information system (GIS)-based modal emissions model being developed with EPA and Georgia Tech to account for vehicle load conditions that will significantly improve the spatial resolution of emissions estimates. (NOTE: Current mobile source emissions models do not directly account for high power and load conditions that produce significant emissions. Studies have shown that a single sharp acceleration may cause as much pollution as the remaining trip and that a small percentage of a vehicle's activity may account for large shares of a vehicle's emissions. Other modal events, such as deceleration or operations on a grade, also appear to produce significant emissions, potentially increasing gram/second emissions by more than tenfold.) The GIS-based modal research model employs detailed subfleet engine and emissions characteristics and the speed/acceleration profiles for vehicle activity along links in the transportation system. Composition of the vehicle subfleet affects the amount of emissions produced under various operating conditions, dependent upon the load induced by the vehicle and driver, and the physical constraints of the vehicle. The aggregate modal frequencies are compared across vehicle classes to show differences in how heavy duty vehicles are operated.

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## ABSTRACT

Current mobile source emissions models do not directly account for high power and load conditions that produce significant emissions. Studies have shown that one sharp acceleration may cause as much pollution as the remaining trip<sup>1</sup> and that a small percentage of a vehicle's activity may account for large shares of a vehicle's emissions.<sup>2</sup> Other modal events, such as deceleration or operations on a grade also appear to produce significant emissions, potentially increasing gram/second emissions by more than tenfold.<sup>3</sup> A new geographic information system (GIS)-based modal emissions model being developed by Georgia Tech with the Environmental Protection Agency (EPA) is designed to account for vehicle load conditions and will significantly improve the spatial resolution of emissions estimates.

The GIS-based modal research model employs detailed subfleet engine and emissions characteristics and the speed-acceleration profiles for vehicle activity along links in the transportation system. Composition of the vehicle subfleet affects the amount of emissions produced under various operating conditions, dependent upon the load induced by the vehicle and driver, and the physical constraints of the vehicle.

The speed-acceleration activity profiles of vehicle operations on roadways are hypothesized to depend on characteristics of the traffic stream, physical characteristics of the roadway, characteristics of the drivers, and physical characteristics of the vehicles. Using instantaneous positional information recorded from a laser rangefinder, representative speed-acceleration operating mode frequencies for different classes of vehicles for different roadway classifications are currently being developed. In this paper, the aggregate modal frequencies are compared across vehicle classes to show differences in heavy-duty vehicle operation, and the likely impact of physical characteristics of the roadway or classification of the vehicle on operating mode frequencies. The findings from the study do show that differences in operating modes are apparent across different classes of heavy-duty vehicles and that geometric characteristics of the roadway affect modal frequencies.

## INTRODUCTION

National policy and local strategies for improving air quality are tied closely to changes in motor vehicle technology and transportation system operations. Hence, a great deal of regulatory and research attention is focused on improving estimates of the mobile source emission inventory contribution. For example, the U.S. EPA Federal Test Procedure (FTP) improvement project is redesigning the certification process to better represent on-road driving and emissions.<sup>4</sup> Multiple cycle modeling approaches may be used to develop emission testing cycles for various roadway classifications so that fleet emission rates can be applied to the associated activity, based on the roadway class and current level of service. An engine map approach translates real-time speed and route information into vehicle revolutions per minute (rpm) and load parameters to relate instant emission rates for the current condition.<sup>5</sup> The physical modal emissions

model estimates emissions from analytical functions used to describe the operation of the vehicle and the process of production of emissions.<sup>6</sup> Finally, statistically based modal models disaggregate vehicle activity into modes of operation such as acceleration, deceleration, idle, and cruise, and develop emission rates for each activity.<sup>7</sup>

The last approach, the development of a statistically based modal emissions model, seems to be generally accepted as the best structure for an emissions model that represents what actually occurs during motor vehicle operations. Inherent in such a modeling approach, however, is the concept of replacing a nominal driving cycle with vehicle operating mode distributions. This raises the issue of the degree to which there are differences in modal frequencies across different vehicle classes. The purpose of this paper is to determine if differences in modal frequencies exist in one type of vehicle in the fleet, heavy-duty vehicles. Of particular interest is to determine if differences in modal frequencies exist, and if the observed differences can be related to the physical characteristics of the road and the classification of the vehicle.

## **EMISSIONS MODEL CONCEPT**

Before discussing heavy-duty vehicle operating modes, it is first important to understand the general structure of the mobile emissions model, and the integration of heavy-duty vehicles into the model. Georgia Tech, sponsored by and in cooperation with EPA and a number of other partners, has been developing a modal emissions model. The basic point of departure of the research model from conventional models is that mobile source emissions are associated with certain types of engine and vehicle modal operations (cruise, acceleration, deceleration, idle, and power demand) rather than average speed. By modeling emissions from specific modes of vehicle operation and replacing a "driving cycle" with operating mode distributions, the level of aggregation used with composite emission factors is reduced.

The overall conceptual framework that guides the Georgia Tech/EPA modal model is provided in Figure 1. Fleet composition is generated by link and zone for the transportation network and by zone for off-network activity. Profiles of vehicle activity on and off the network are estimated in terms of the distributions of emission related vehicle, operating, driver, and environmental characteristics. Vehicle activity data, such as modal profiles, are linked with previously derived emission rate relationships that account for the subfleet characteristic distributions and operating characteristic distributions to estimate emissions for each link and mini-zone.

The research model is developed on a GIS platform. The GIS is a system for storing all of the spatial and temporal attributes of the modeling regime, integrating a wide variety of data sources, spatial attributes, and temporal distributions for use by external programs to estimate emissions. The coded GIS contains the transportation network physical characteristics (link length, number of lanes, grade, etc.), terrain, roadway operational characteristics (capacity, vehicle mix, etc.), analysis zones, intersections, on-ramp locations, and other point sources of potential enrichment activity. The new model is a step beyond current emissions modeling techniques, requiring an abundance of memory and computing power within the GIS to process data. The process of developing relationships will incorporate uncertainty estimates and use of existing databases, such as the Federal Highway Administration's (FHWA) highway performance monitoring system (HPMS), coverage counts, and inspection/maintenance databases.

Information on the vehicle characteristics and operating mode characteristics expected to be necessary to implement the modal model will be expanded under individual headings of Figure 1. For example, vehicle subfleets must include information on the distribution of model years, vehicle weights, vehicle technologies, and other critical parameters so that appropriate estimates of super-emitting vehicles can be derived. Operating mode profiles include such aspects as grade and acceleration distributions so that frequency distributions for enrichment events can be derived. Figure 2 is a graphical description of the "modular" development of the emissions model, where the different modules are contained within the GIS, sharing many of the same attributes to compute emissions from different portions of vehicle activity. It is within this modular framework that heavy-duty vehicle activity will be estimated.

### **Heavy-Duty Vehicles Module**

The vehicle activity patterns and emission rates for heavy-duty trucks and buses are completely different than those of light-duty vehicles, so computation of emissions is undertaken in a separate emission rate module. The heavy-duty truck module in the research model will combine the results of a number of vehicle activity research studies being undertaken in Atlanta designed to better quantify truck activity both on and off the road network. Heavy-duty truck activities will be allocated to the network and industrial/commercial zones in the GIS framework and employed in emissions estimation. Over the short term, existing heavy-duty vehicle emission rates from MOBILE5a will be integrated directly into the module. However, existing heavy-duty truck emission rates and correction factors have been questioned in the past by the research community<sup>8</sup> and remain in the top five transportation/air quality research needs identified by the Transportation Research Board. A new effort is underway at the EPA's Office of Research and Development in Research Triangle Park to better quantify the emission rates of on-road heavy-duty trucks under a variety of operating and load conditions. The new modal emission rates will be integrated directly into the new modal emissions modeling regime as they become available. Modal frequencies of trucks will be applied in the same manner as light duty vehicles, as a function of the characteristics of the roadway, driver, and traffic conditions present on the road.

The operation of buses in an urban area is much simpler to represent compared with the operation of automobiles. Schedules are well established by the regional transit authority. Activity in terms of time of operation and route of operation is regular and known. Modal frequencies of buses will be collected in unison with the heavy-duty vehicle activity to classify activity for prediction of emissions.

Motor vehicle emissions are modeled on a second-by-second basis as a function of the variables that affect emission rate magnitude. Current research involves investigation into speed-acceleration distribution, grade, engine load, and throttle position. Individual emission rates for light-duty vehicles are divided into operating regimes, normal operations, enrichment operations, and enleanment operations. Emission rates for heavy-duty vehicles are modeled as a function of engine load (grams/brake-horsepower-hour), a function of engine characteristics, vehicle load, and operating conditions. Data collection under a modal emissions modeling approach for heavy-duty vehicle operations must relate to variables likely to contribute to emissions emitted from the various classes of vehicles.

### **MODAL ACTIVITY INVESTIGATIONS**

Previous studies at Georgia Tech have quantified speed-acceleration frequencies at intersections, ramps, and freeway segments using laser rangefinders.<sup>9</sup> The ramp modal frequency portion of the study stratified

the data collection into four parts based on grade (<-2 %, -2% to 0%, 0% to 2%, and >2%). The net results of occurrence of speeds and accelerations at these different grades were combined into one chart of frequency of all possible speed-acceleration combinations. The freeway segments and intersections were studied in a similar manner, with sample stratification by volume for the segments and level of service for the intersections. Results of this study provide an initial understanding of modal distributions, but do not quantify how any other variables such as lane geometry, traffic volume, and vehicle mix, affect frequency of modal operations, or the differences in operating mode profiles experienced by different classes of vehicles.

The geometric considerations of ramps on vehicle modal activity were also investigated by California Polytechnic State University through use of video tape analysis, and the results showed that modal profiles are significantly affected by many geometric variables, including grade, curvature, length, and mainline traffic considerations.<sup>10</sup> "Smoother" vehicle performance was found on ramps with significant curvature and auxiliary lanes; and no difference in vehicle performance was found due to moderate grade differences on short ramps. Vehicle performance along on-ramps was found to be independent of mainline traffic. However, some drivers were more "erratic" than others upon approaching congested mainline traffic.

In developing truck modal frequencies for use in a modal emissions model, care must be taken to ensure that results are representative of "real world" modal tendencies of various classes of trucks. Omitting a small percentage of high load or high acceleration operations would result in omission of a large percentage of emissions over the road. Hence, rare events must still be modeled and must be captured in the data collection process.

## EQUIPMENT

The laser gun used in the study is a ProSurvey 1000 laser rangefinder (LRF) capable of tracking vehicles for distances up to 4500 feet\*, with an internal programmable algorithm which converts the range readings into speeds with relative time stamps. Several different modes of ranging are available on the ProSurvey laser gun which are well suited to tracking speeds and accelerations of vehicles. Real-time ranging transmits range data at the maximum firing frequency of the laser gun (238 times per second). The real-time ranging mode also allows for fast two byte transfer of the data via an RS-232 connection. Connecting the RS-232 to a laptop computer allows the user to download the information directly to hard disk for storage.

The LRF has different operating modes in which data can be saved on the laptop computer: real-time-range (RTR) mode, range average (RAVG) mode, and speed (SPEED) mode. RTR mode returns a range every shot, at 238 times a second. This rate of transfer is too fast for the computer to store every value using the supplied vendor software. RAVG mode takes readings over a specified interval and averages the readings. The average over the interval (number of consecutive shots) is dependent on how the readings are binned and the number of occurrences in each bin. The returned value in RAVG mode is not a true mean of every return from the interval but based on the distributions of valid readings. SPEED mode takes readings and computes speeds every set interval, but uses a smoothing mechanism in which previous measurements are averaged with the current interval. This smoothing procedure

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\* Readers more familiar with the metric system can use the following conversions: 1 ft = 0.3 m, 1 mi = 1.609 km.

results in speeds that do not always represent the actual speed for the time interval; thus computation of true acceleration is imprecise.

Because of loss of data and inconsistent readings with the manufacturer supplied software, a C program was written to capture the RTR binary format directly to the computer hard drive. The program is based on Raid Breiwish's program used in the previous speed-acceleration study at Georgia Tech,<sup>9</sup> slightly modified to account for the higher baud rate and different frequency of the newer LRF. In addition, a processing program was written to transfer the captured binary data into usable text form. Initial studies with this form of data capture indicate nearly 100% data capture rate and the ability to read data into any format.

Field testing has initially shown limitations on the range at which the laser rangefinder can track truck activity. The distance that trucks can be tracked is limited by line of sight, obstructions such as light standards, trees, and signage, as well as interference from other traffic. The maximum distance at which the laser will "lock on" to a truck is approximately 2300 feet, with consistent data being returned as the truck is closer to the LRF. Distance is more of a problem in heavy traffic and for tracking automobiles for any considerable period. More reliable data will be returned from trucks because of the large front or rear area they provide for computing ranges.

Mainline, traffic count, and vehicle classification data are collected at the site using a Jamar Technologies, Inc., TDC-8 traffic collection board to provide supplementary information on traffic stream characteristics. The Jamar board provides a specific time stamp along with each individual keystroke. Hence, unique data buttons are used to classify the type of vehicle being tracked by the laser gun. In the office, the laser gun data and the Jamar data can be compared by time and order to identify which vehicle speed traces belong to which type of vehicle.

## **DATA**

The FHWA Scheme F classification classifies vehicles in 13 categories, with trucks classified by the number of units and axles (Table 1). Trucks are classified into nine categories, and buses into one category. Recording the type of vehicle is completed using a Jamar board with a vehicle classification template. Each time a vehicle trace is recorded by the LRF, the type of the vehicle is recorded by pressing the proper button on the Jamar board. Use of a Jamar board allows for collection of activity from multiple types of vehicles.

The data presented in this paper were collected from two on-ramps with different geometric conditions. The physical characteristics of site 1 are an on-ramp with a moderate length uphill grade leading to four lanes of traffic on an inner city interstate in Atlanta. Site 2 is a long one-lane on-ramp with a downhill grade merging with four lanes of interstate traffic in a northern suburb of Atlanta. Data from each site were collected on two separate days prior to the start of the afternoon peak period (mainline traffic exiting the central business district), with about one week separating data collection of the two sites.

Collection of vehicle activity started when the vehicles were approximately 200 feet from the start of the on-ramp and continued until the vehicle was out of range of the LRF, or obstructed from view by other traffic. Being the start of the afternoon peak period, the majority of the vehicles on the on-ramps were light duty vehicles. The majority of the heavy-duty vehicles and buses along the ramps were recorded

because of the infrequency (as compared to light-duty vehicles). For vehicle classes 10 through 13, there were no types recorded by the LRF, and classes 4, 6, 7, and 8 were infrequent; thus conclusions about observed activity will not be compared to other classes of vehicles until additional data can be collected.

The data for each site were downloaded and processed in the office for calculation of modal distributions. Using the data from the Jamar board, each trace recorded by the LRF could be assigned a vehicle class. The speed and acceleration traces for each class were combined to form a matrix of occurrence, where speeds were in 5 mph bins and accelerations were in 1 mph/sec bins. In addition to keeping the data from each class of vehicle separate, data for each site were kept independent.

Operating modes can be plotted in a three-dimensional Watson plot, with speed on the x-axis, acceleration on the y-axis, and frequency on the z-axis. Thus the area underneath the curve will equal 1, or 100% of the activity occurring at the site. The majority of the data occurred in two vehicle classes, the 2-axle, 6-tire single unit (Figure 3) and the 5-axle double unit (Figure 4). Although no significant high speed, high acceleration combinations were collected from these heavy-duty vehicles (HDVs) at the two sites, the smaller single unit trucks showed higher speed-acceleration combinations and very little deviation from the mean bin. Some of the large 5-axle double unit trucks actually showed decelerations as they reached the peak of the grade approaching the interstate, and the frequency for lower speeds and slower accelerations was greater.

The activity at site 2 was recorded for a longer duration (due to site conditions) and tracked vehicles were entering the mainline traffic just as the LRF cut off. Figures 5 and 6 give the three-dimensional speed-acceleration Watson plots for vehicle classes 5 and 9. At this location, the physical conditions of the site caused fewer negative accelerations, and higher speed and acceleration combinations. HDV class 5 recorded several decelerations, but also several high accelerations with the majority of the activity occurring between 1.0 and 2.5 mph/sec. The activity of the larger 5-axle trucks was more uniform, with no observed accelerations higher than 3.5 mph/sec and only a few seconds of activity in deceleration mode.

Combining all the HDV observations at each site into one plot is shown in Figures 7 and 8, with Figures 9 and 10 giving a two-dimensional view of the plot (note that the ranges of speed and acceleration for these two figures are identical). Areas of similar frequency at site 1 are shifted up and to the right in the plot for site 2. The shift in frequencies is an indication that the modal frequencies of heavy-duty vehicles will depend not only on the classification, but also on physical characteristics of the road and/or driver.

## **IMPLICATIONS FOR A MODAL MODEL**

The purpose of this paper is to determine modal frequencies of heavy-duty vehicles, and the likely impact of physical characteristics of the roadway or classification of the vehicle on distribution of operating modes. The data presented in this paper found variations in modal frequencies across heavy-duty vehicle classes and variations in modal frequency due to site location. On-going data collection efforts will quantify if differences exist between all ten classes of heavy-duty vehicles, and what type of traffic and geometric conditions influence modes of operation. Indications from collected data show that larger

trucks have limitations as to maximum accelerations and can actually decelerate at a location where the physical characteristics of the road dictate an expected acceleration.

Differences in modal frequencies were observed across two sites with different geometric characteristics. This leads to the next phase of the modal frequency study where collection of data will correlate the activity profiles of vehicle operations on roadways based on characteristics of the traffic stream, physical characteristics of the roadway, characteristics of the drivers, and physical characteristics of the vehicles (classification, weight, etc.). Thus, a systematic data collection of activity will yield operating mode frequencies for locations with definable physical characteristics.

By replacing a nominal driving cycle with vehicle operating mode distributions, one eliminates the need of using driving-cycle-based composite emission factors, and the emissions can be based on observed tendencies of vehicles. Speed-acceleration frequencies along links of the transportation system combined with vehicle subfleet engine and emissions characteristics can yield estimates of emissions based on observed modes of operation. Composition of the vehicle subfleet will affect the amount of emissions produced under various operating conditions, dependent upon the load induced by the vehicle and driver, and the physical constraints of the vehicle. Developing operating mode frequencies of vehicles at points of high load conditions and probable enrichment (ramps, weaving areas, intersections) into mobile emissions models will yield emission estimates by replacing average speed with the operational mode of the vehicle.

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Table 1. FHWA Classification, Scheme F

Vehicle Class	Description
1	Motorcycles
2	Cars, +/- trailers
3	Pickups, vans, motor homes
4	Buses
5	2-axle, 6-tire single unit
6	3-axle, single unit
7	4-axle, single unit
8	4 or less axles, double, 1 unit is truck
9	5-axle, double, 1 unit is truck
10	6 or more axles, double, 1 unit is truck
11	5 or less axles, multi-unit
12	6-axle, multi-unit
13	7 or more axles, multi-unit

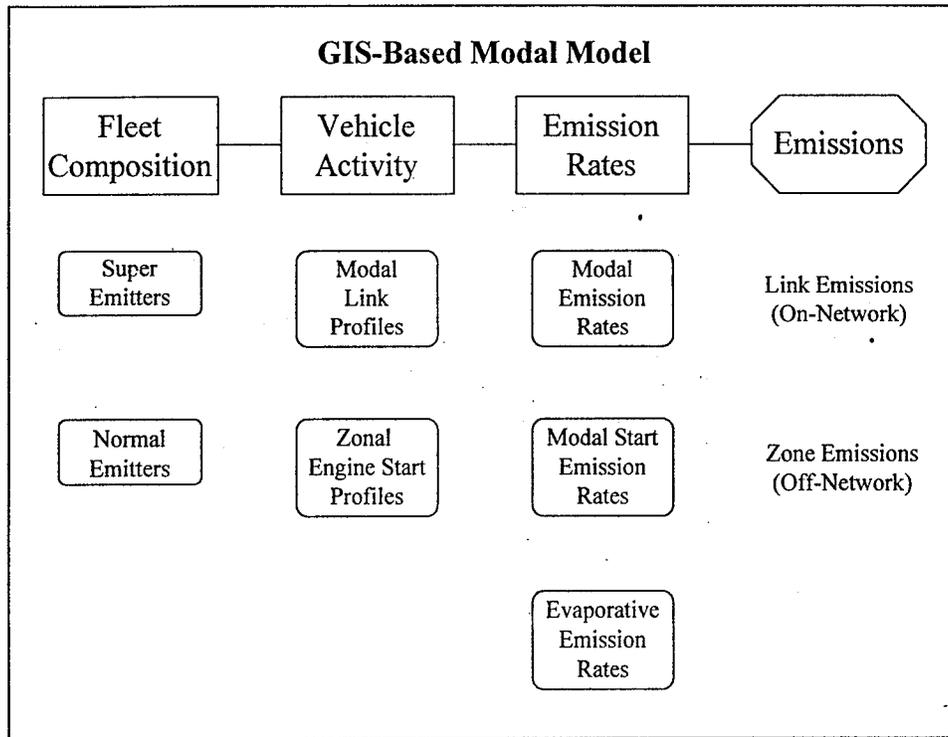


Figure 1. GIS modal model conceptual development for prediction of emissions. <sup>7</sup>

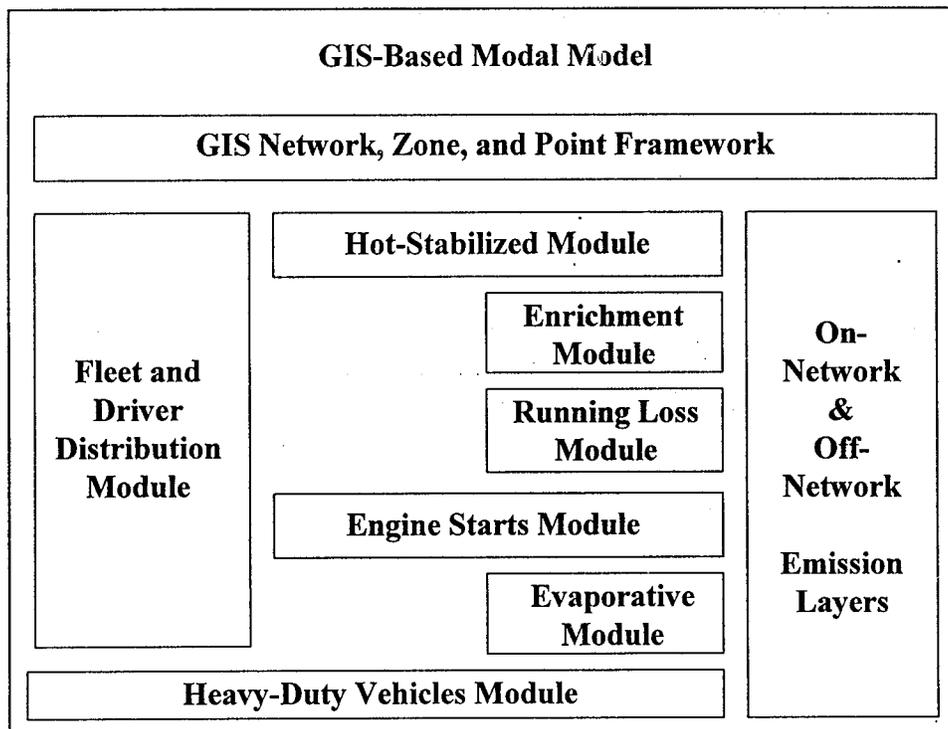


Figure 2. GIS modal model development, module integration. <sup>7</sup>

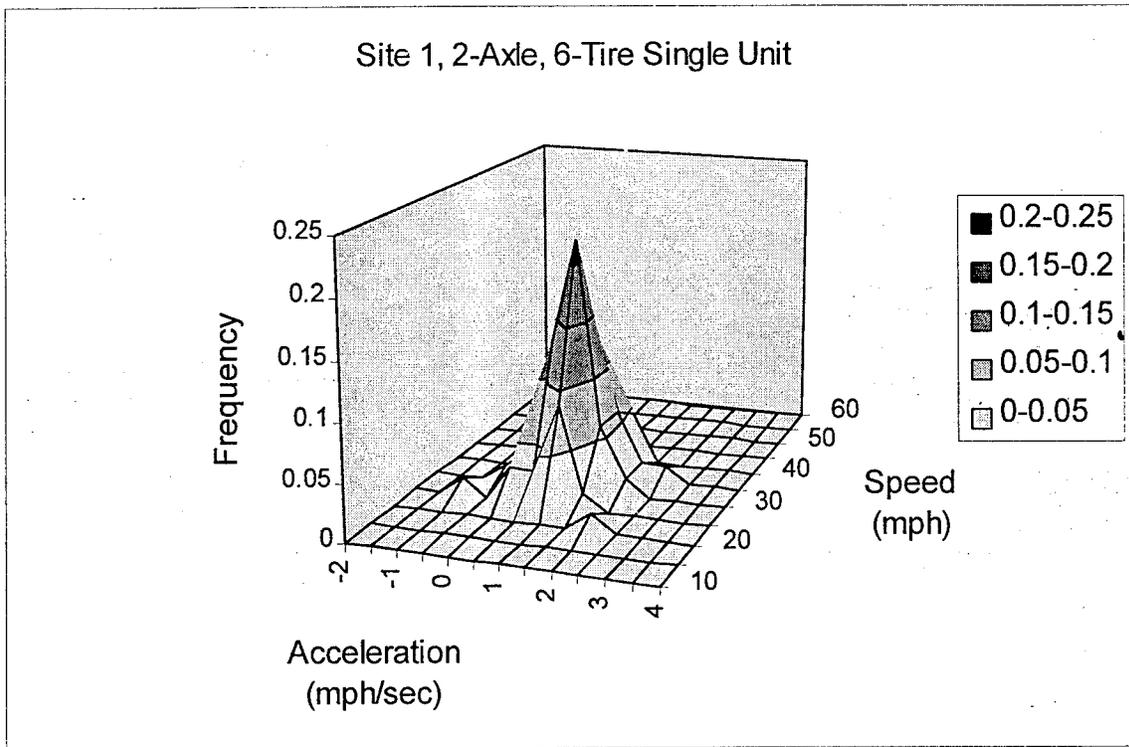


Figure 3. Two-axle, six-tire single unit truck activity profile at site 1.

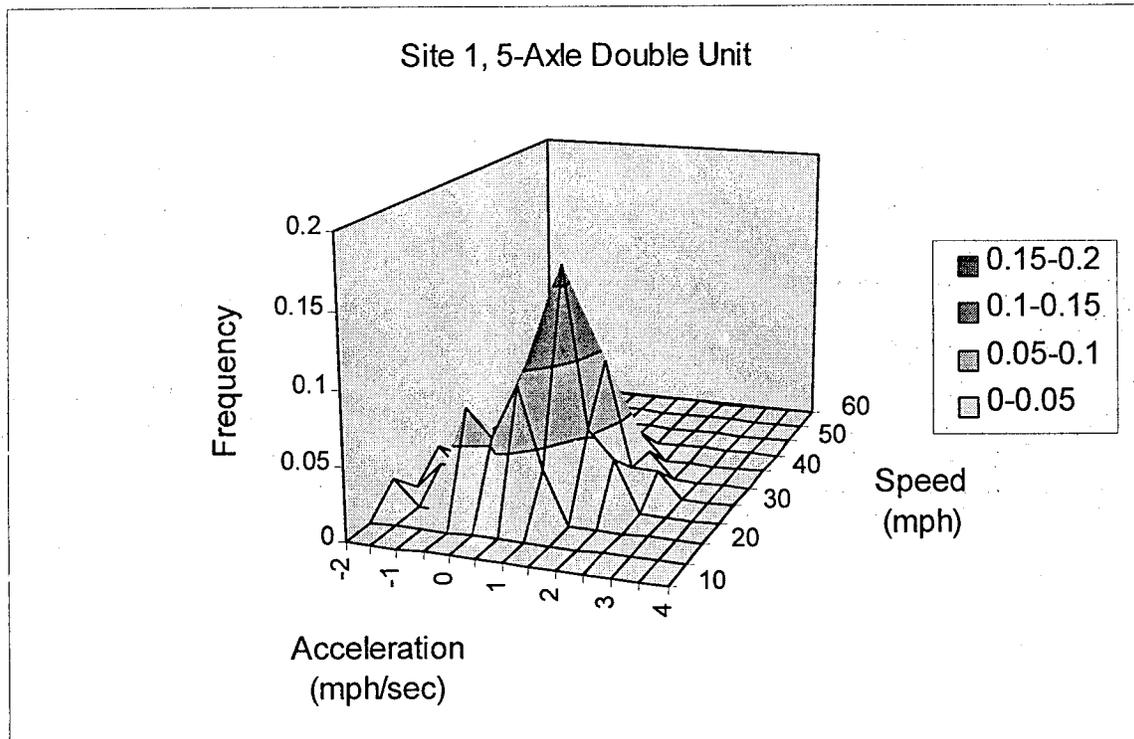


Figure 4. Five-axle double unit truck activity profile at site 1.

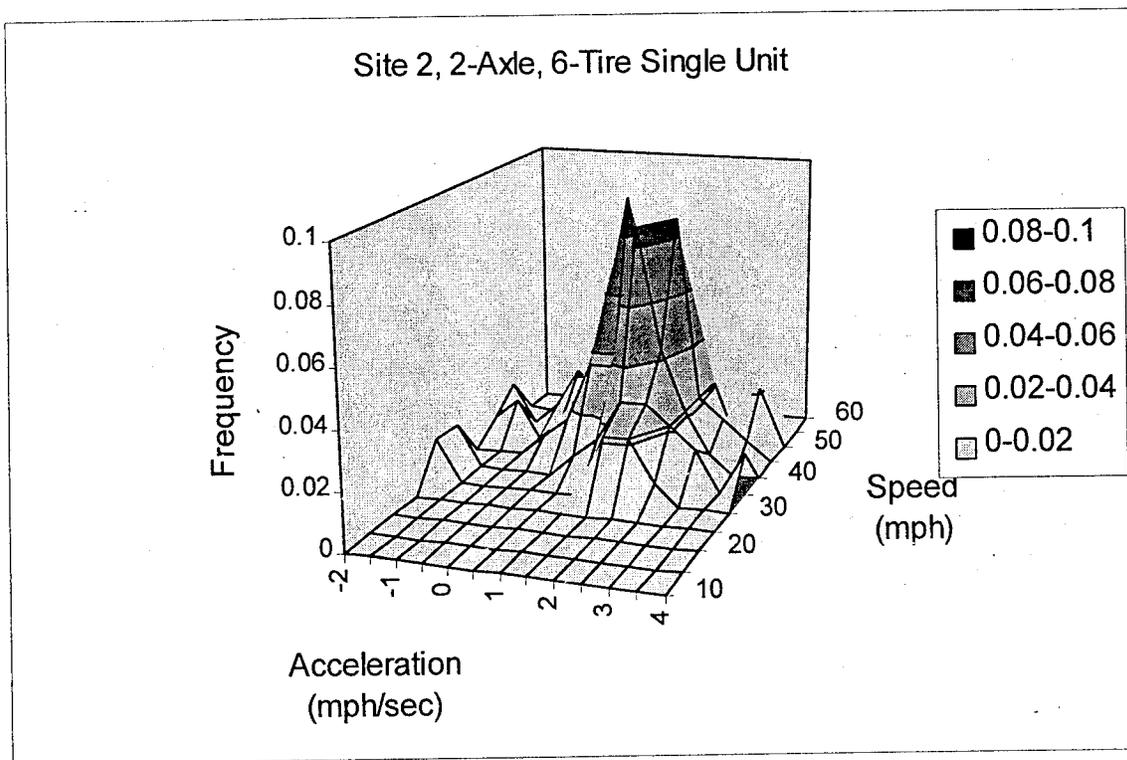


Figure 5. Two-axle, six-tire single unit truck activity profile at site 2.

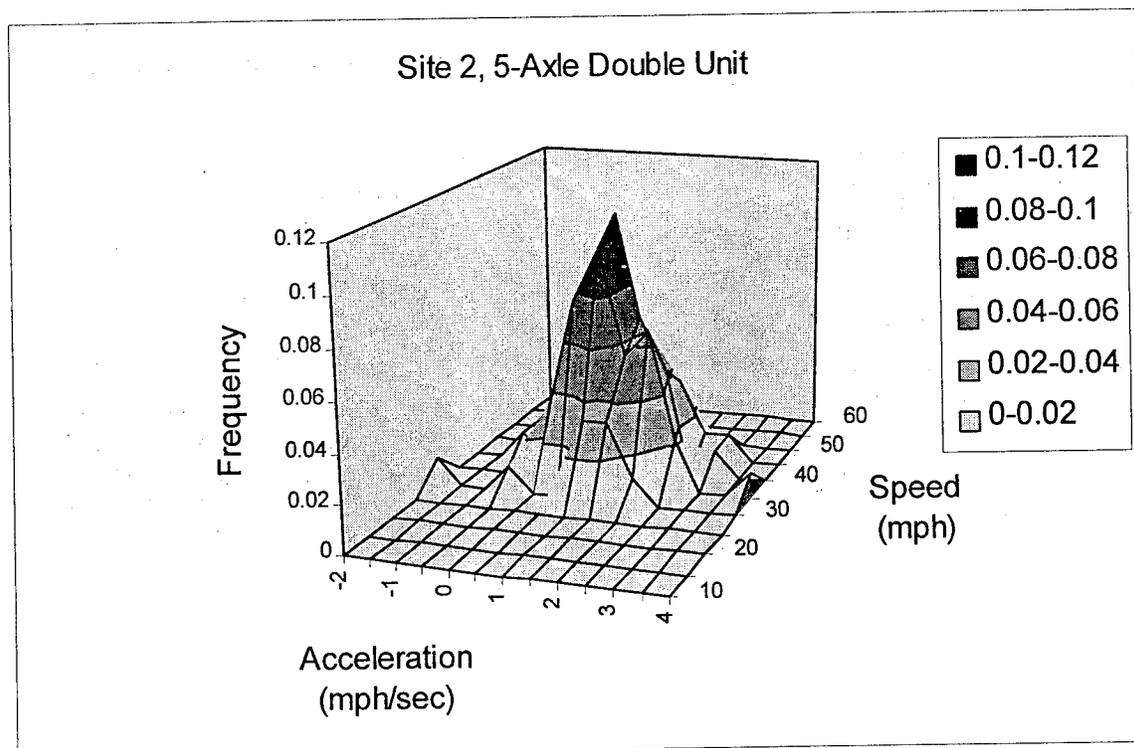


Figure 6. Five-axle double unit truck activity profile at site 2.

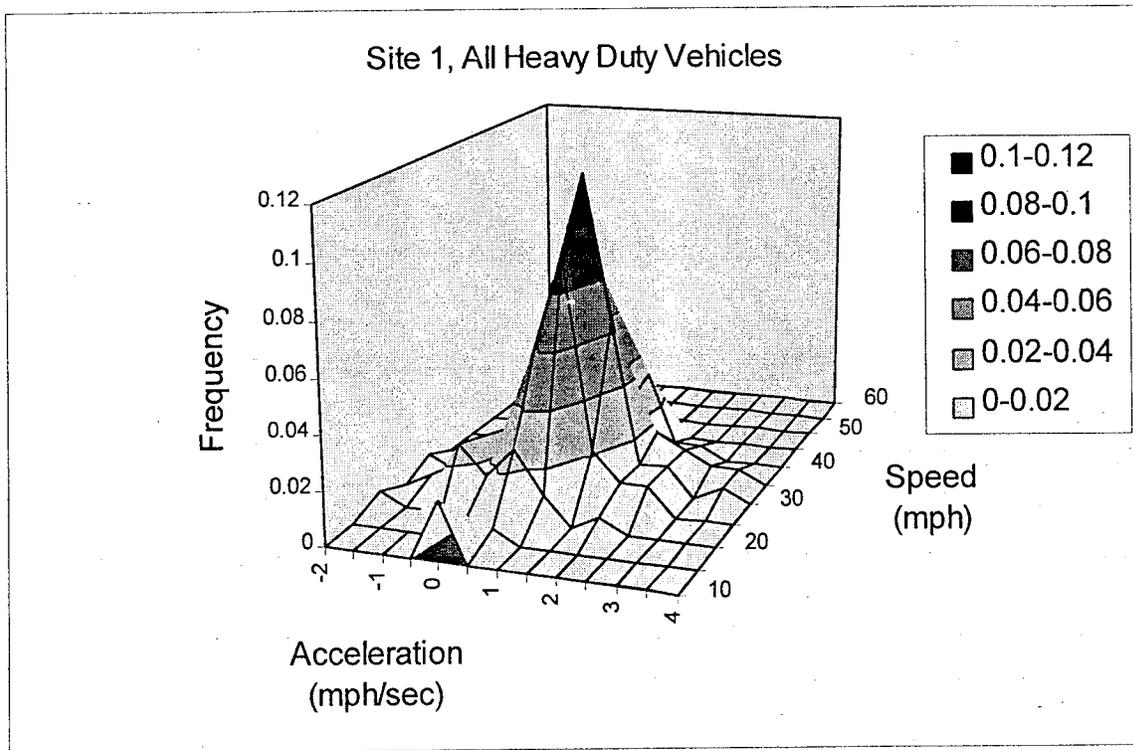


Figure 7. Combined heavy-duty vehicle observations, site 1 (Three Dimensional Plot).

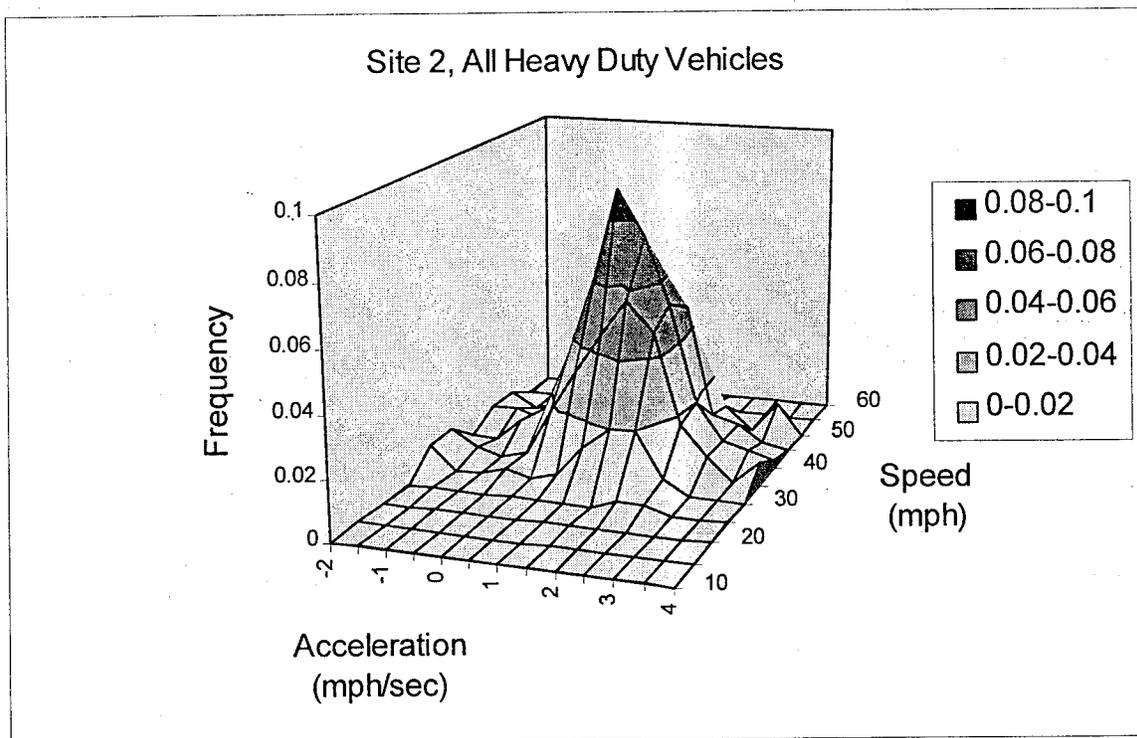


Figure 8. Combined heavy-duty vehicle observations, site 2 (Three Dimensional Plot).

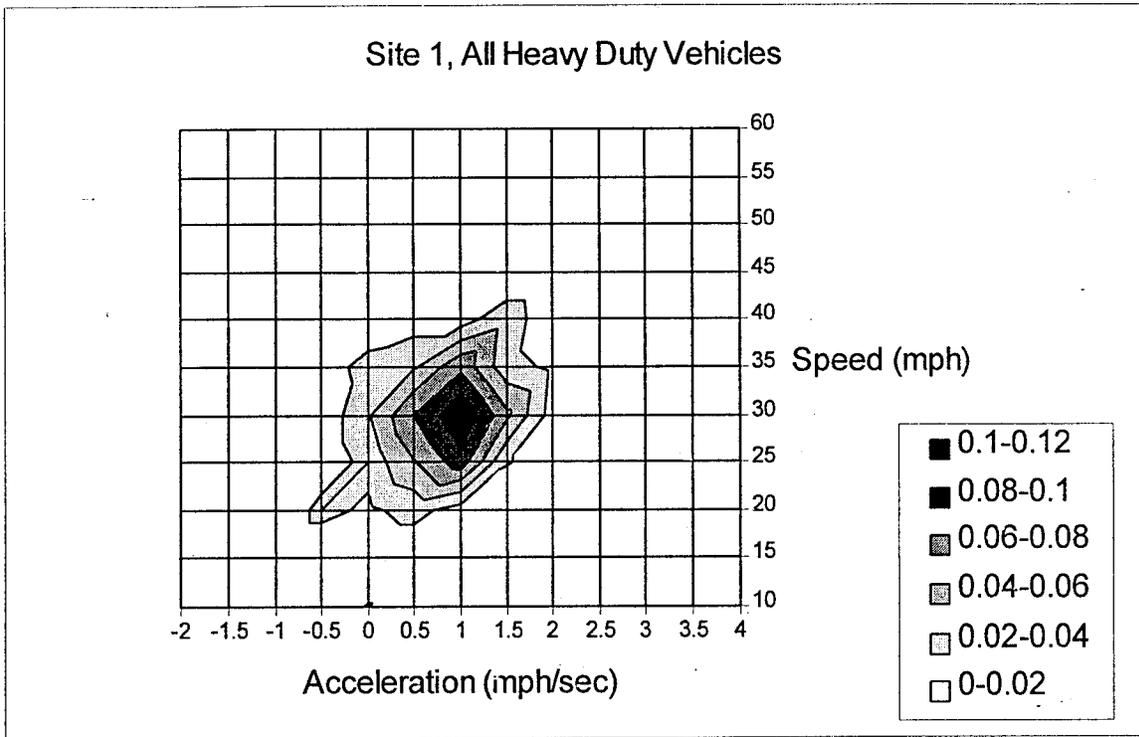


Figure 9. Combined heavy-duty truck observations, site 1 (Two-Dimensional Plot).

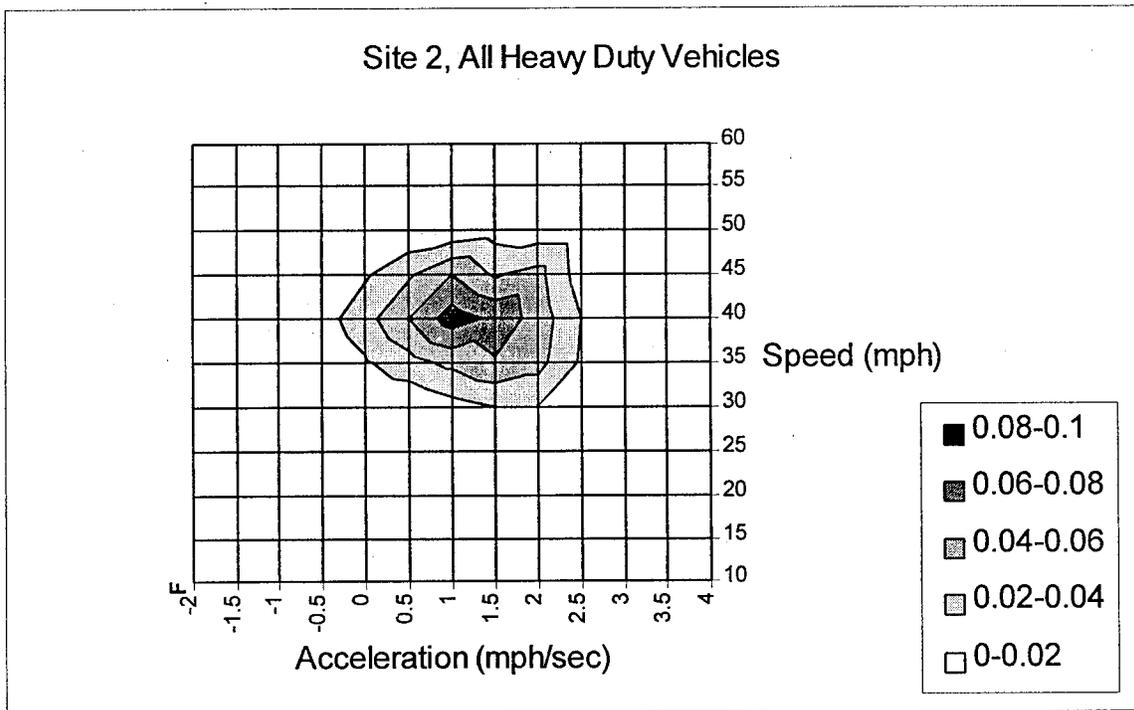


Figure 10. Combined heavy-duty truck observations, site 2 (Two-Dimensional Plot).