

## Heavy-Duty Truck Activity Research in Atlanta

Dike Ahanotu  
Todd Bettger  
Randall Guensler, Ph.D.  
Michael D. Meyer, Ph.D.  
Chris Grant

School of Civil and Environmental Engineering  
Georgia Institute of Technology  
Atlanta, GA 30332-0355

### ABSTRACT

Both transportation and air quality planners recognize that heavy-duty truck activity contributes significantly to the transportation system of a given region. However, existing heavy-duty truck activity estimates are highly uncertain, and methods currently fail to consider specific vehicle and operating characteristics that are needed in next generation motor vehicle emissions models. Specific fleet characteristics and activities which produce elevated emission rates are not currently modeled in the emission inventory process, and are likely to contribute to emission inventory misrepresentation. Modeling the distribution of operating modes (cruise, acceleration, deceleration, idle), engine horsepower, and vehicle load distributions are important emission parameters that are not included in current models. Future modal emissions models will utilize more detailed information on subfleet characteristics, speed-acceleration mode frequencies, fleet engine horsepower distributions, and spatial and temporal distributions of truck load factors. The objective of this paper is to describe the data collection efforts underway in Atlanta which will be used in the next generation of heavy-duty emissions modeling. First, the sources of uncertainty in previous models is discussed. Then, the ongoing truck activity studies in the Atlanta metropolitan region (vehicle classification, speed/acceleration profile, and truck weight distribution studies) are outlined and initial results are discussed.

### INTRODUCTION

Knowing the composition of the vehicle fleet is a critical input into transportation planning and air quality analysis. In local transportation project development, this fleet composition determines such critical parameters as pavement thickness, radius of curvature for curves on highway alignment, and permissible grades for vertical curves. In response to this data requirement, transportation agencies have developed several data collection strategies to determine the different types of vehicles likely to traverse a single link in the road network. However, for regional transportation planning (and its linkage with regional emission estimation), which is concerned with large scale movement of vehicles within and through metropolitan areas, transportation agencies have generally

not provided a similar level of detail on expected traffic fleet composition. This is especially true for heavy-duty vehicles which have generally been "modeled" as a simple fraction of the light-duty vehicle traffic, a fraction estimated from observed vehicle classification counts at various locations in the network.

For transportation planners, this paucity of data on heavy-duty vehicle activity is a serious barrier to effective planning under the requirements of the Intermodal Surface Transportation Efficiency Act (ISTEA) which requires a planning emphasis on the movement of commercial freight vehicles in a metropolitan highway network. For air quality analysts, these same data can improve the emissions estimate associated with heavy-duty vehicles, an element of the mobile emissions inventory that research is showing as having potentially important contributions to emissions levels.

The purpose of this paper is to describe a comprehensive effort underway in Atlanta to significantly improve truck activity estimates and operating profiles. The objectives of the ongoing truck activity studies are to:

- 1) Define interstate, intercity, and local truck fleet characteristics by truck classification.
- 2) Estimate temporal and spatial distributions of heavy-duty truck activity.
- 3) Link vehicle loads with spatial activity data for emission rate modeling purposes.
- 4) Estimate heavy-duty vehicle speed/acceleration profiles for Atlanta freeways and arterials also for emission rate modeling purposes.

To accomplish these objectives, data are being collected from numerous public agencies and private companies. Field data are also being collected with a laser rangefinder to create speed/acceleration profiles. Supplemental data will be collected to gather information on vehicle classification and weight distributions at critical locations where data are not readily available.

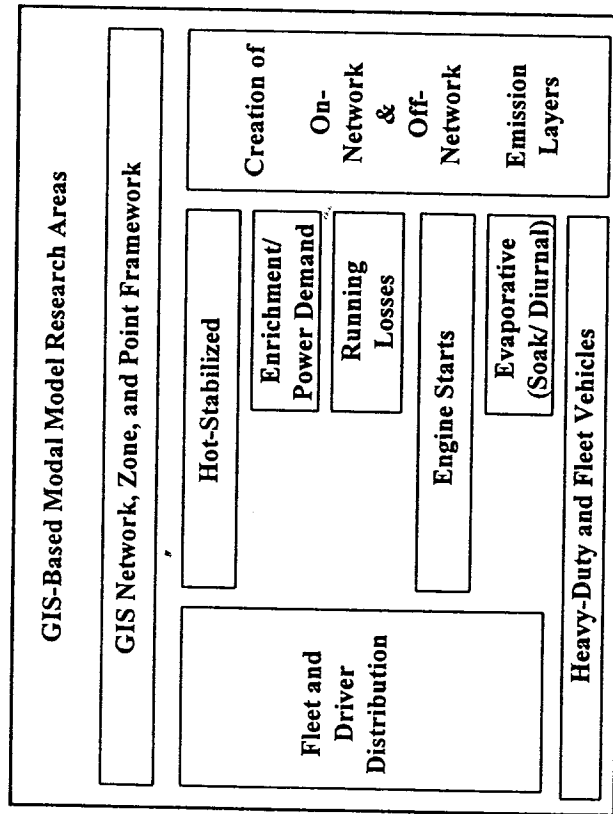
Future data collection activities will also be aided by the Georgia Department of Transportation's (GDOT) Advanced Traffic Management System (ATMS). The ATMS will have video surveillance and automated data collection activities at approximately 50 locations in the Atlanta freeway system and will provide data on vehicle classifications, volumes, and speed/accelerations. Data collection efforts will continue through the summer of 1996. Therefore, the results presented in this paper are preliminary in nature. The complete results will be reported in subsequent papers.

### HEAVY-DUTY VEHICLE ACTIVITY IN EMISSIONS MODELING

Emission levels from motor vehicles relate to how vehicles are operated as well as the conditions under which vehicle operations occur. Estimates of operating emissions from any vehicle are a function of two sets of parameters: emission-producing vehicle activity and activity-specific emission rates. The current development of new emissions

model is primarily based on a modular approach wherein each type of engine mode found to have important contribution to overall emissions is modeled with modal-specific emissions rates and activity factors. Figure 1 shows the modal modeling research categories being pursued in a research program at Georgia Tech to develop improved emission inventory estimates. Each of the emission modules represents an important activity in emissions generation that is found to have a potentially significant impact on mobile emissions estimation. Many of the modules are linked by common input data relating to vehicle activity, and the overall emissions estimate is provided by combining different layers in a geographic information system (GIS). Note in Figure 1 that heavy-duty vehicle emissions is a separate module with specific input data requirements.

Figure 1:



There are many sources of uncertainty in both the existing activity estimates and emissions factors used to estimate the emissions contributions of heavy-duty vehicles (Guenster, et al., 1992; Guenster, et al., 1991; Nelson, et al., 1991). With respect to heavy-duty truck emission rates, engine dynamometer emission test results from a small sample of engines yielded highly uncertain emission rates. Emission rates do not explicitly consider engine maintenance or differences in fuel properties. Plus, modeled emission rate correction factors do not appear likely to be representative of actual relationships between engine characteristics, operating modes (engine load and speed/acceleration activity), and emissions.

The sources of uncertainty in heavy-duty vehicle activity are centered around the basic lack of information about the temporal and spatial distribution of the various truck activities. For air quality modeling purposes, it is necessary to specify vehicle activity by location and time of day. Temporal distributions are also needed for seasonal calculations. For example, trucking activity may be high in the fall due to the expected increase in retail activity during Christmas. Very little, if any information exists for a number of critical vehicle activities, such as truck engine starts, engine idling, and high power demand activity, thus adding to the uncertainty associated with the overall estimate of heavy-duty vehicle activity.

New emission rate studies being conducted in California and North Carolina with second-by-second chassis dynamometer testing and instrumented vehicles will yield significantly improved emission rate algorithms for heavy-duty vehicles. It is likely that the new emission rate algorithms will still employ a grams/brake-horsepower-hour modeling approach for various engine classifications. Hence, understanding the amount of truck activity by truck subfleet, the loads carried by those vehicles, and the speed/acceleration characteristics of the truck activity will be key inputs to the emission modeling regime. However, very little is currently underway to better understand the activity-side of the emissions estimation relationship.

Heavy-duty vehicle activity studies are currently being undertaken in Atlanta to support the implementation of new emission rate modeling algorithms that will be integrated into the regional GIS-based modal emissions model. The results of these studies will also contribute significantly to the development of improved activity sampling, monitoring test methods and improved emissions modeling accuracy.

### TRUCK ACTIVITY STUDIES IN ATLANTA

The Atlanta study has four specific objectives: vehicle classification of the heavy-duty vehicle fleet, statistical analysis of heavy-duty vehicle activity, estimation of spatial and temporal distributions of heavy-duty vehicle load factors, and estimation of spatial and temporal distributions of speed/acceleration profiles. Each research element is described in more detail in the following subsections. The goals of each element are outlined and the data sources already identified by the team are described. Preliminary results from initial studies are presented, as well as descriptions of additional studies already underway or scheduled to begin shortly. Because studies will continue throughout the 1995-96 academic year, research results from each research element will be reported in separate publications.

### Heavy-Duty Vehicle Classification

The motor vehicle emission rates for various vehicle classes can differ significantly. For example, the emission characteristics of gasoline and diesel engines differ markedly. Emission rates from larger engines and smaller engines, and newer engines and older engines differ significantly. Combustion design and emission control technologies continue to evolve. It is thus important to have an emissions modeling

approach with sufficient flexibility to reflect changing technology. In emission rate models, average emission rate values are used to represent emissions from a unit of vehicle activity. These values should be representative of the emissions from the vehicle or group of vehicles they are designed to represent. Modelers usually attempt to group vehicles with like emission characteristics into a technology group and employ an average emission rate for each group, rather than a single value for the fleet. In this manner, as fleet compositions change over time, the emission rates employed for the various groups are also more likely to continue representing the onroad emissions from that vehicle group.

Heavy-duty vehicles are grouped using a classification scheme defined by parameters that affect emission rates as revealed through laboratory and onroad testing. Based upon literature review and analysis of emissions data from US Environmental Protection Agency's Office of Mobile Sources (EPA/OMS), the California Air Resources Board (CARB), and Los Angeles Regional Transit District testing facility, the Georgia Tech study is developing vehicle classifications with similar emission behavior (based upon noted average modal emissions responses and variability in that response). At a minimum, fuel type, gross vehicle weight rating (GVWR), and engine displacement will be employed in the classification schemes. For emissions modeling purposes, it is important to be able to identify the spatial and temporal resolution of emission-producing vehicle activities for each of the vehicle technology groups for which emission rate relationships are being developed.

The primary sources of heavy-duty vehicle fleet composition data for the Atlanta metropolitan region are: the GDOT onroad vehicle classification data, the Georgia Freight Bureau data, and regional weigh station data. Information on the composition of municipal fleets (vehicle characteristics and use locations) is available from various local government offices. Private fleet composition will be identified through vehicle registration data and direct contact with fleet operators. To supplement the existing data, truck classification field studies along major truck routes and within geographic zones where delivery activity is prominent (based upon land use) will be undertaken this fall. Vehicle classification data will be used to establish the truck fleet distribution by time of day, roadway functional class, and specific route locations.

A sample set of vehicle classification data was collected at a weigh station in Douglas County, a suburban county approximately 20 miles from Atlanta. The vehicles were classified by a weigh-in-motion sensor which determined the vehicle class based on a combination of the number of axles and the spacing of the axles. The different classifications of the data included 2-axle single unit (SU), 3-axle SU, 3- and 4-axle Semitrailer (semi), 5-axle semi, 5-axle 2-trailer (5-ax, 2-trlr), 6-axle semi, 6-ax 2-trlr, 7-axle semi, and unclassified vehicles. Figures 2 and 3 illustrate the hourly distribution of different vehicles for portions of two days at this weigh station.

Figure 2 - Douglas County Weigh Station Data, 7/11/95:  
Hourly Vehicle Classification

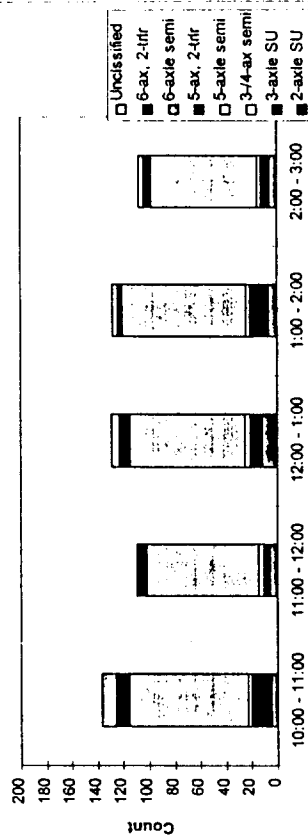
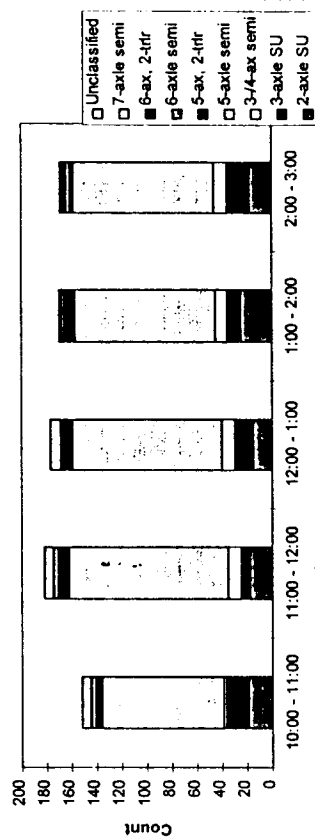


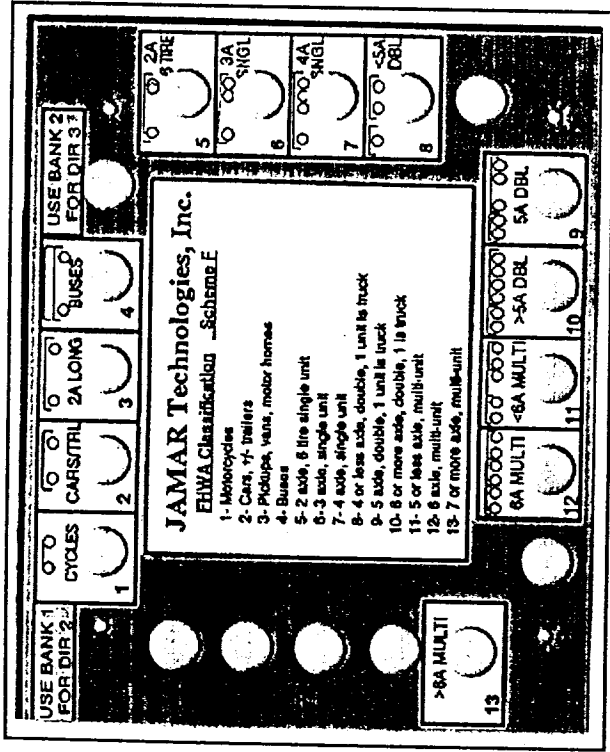
Figure 3 - Douglas County Weigh Station Data, 7/3/95:  
Hourly Vehicle Classification



Initial inspection of the data presented in Figures 2 and 3 indicate that fleet composition has the potential to vary considerably across days and times. Statistical analyses of the temporal variability in truck fleet composition will be undertaken using the data from automated weigh-in-motion stations as these data become available.

Hand counts of truck classifications are also undertaken using JAMAR electronic counting boards. These counters can be utilized to conduct a vehicle classification study using the Federal Highway Administration's Type F Vehicle Classification Scheme. This scheme groups vehicles into thirteen classes, based on number of axles, length of vehicle, and number of individual units that make up the vehicle. A template displaying this scheme can be placed on the board to facilitate data collection (Figure 4). The board stores the data as a file, which can be brought back to the office and downloaded into a PC using native software.

Figure 4: JAMAR Board with FHWA Type F Classification Template



### Heavy-Duty Vehicle Activity Analysis

The next generation of motor vehicle emissions model will require estimates of truck trips, engine idling, network truck traffic volumes, and conditions under which the vehicle miles of travel were undertaken.

In many urban areas, estimates of truck vehicle miles of travel (VMT) are based upon total traffic counts (typically axle counts or vehicle counts, depending upon the sensor technologies employed), and assumed and/or monitored vehicle classification estimates. The Planning and Data Services Division of GDOT provide data on truck weights using weigh-in-motion scales at approximately 15 sites in the state. These data are recorded onto optical disk and sent to the Federal Highway Administration as part of a federal bridge monitoring program.

Truck terminals that handle more than 100 truck movements per day in each direction have been identified in the Atlanta Metropolitan region for the purposes of developing the regional intermodal management system under the Intermodal Surface Transportation Efficiency Act. These truck terminal locations have been geo-coded and will be used for a variety of purposes in developing vehicle activity profiles for the Atlanta region. For example, the terminal locations provide a basis for the identification of high traffic truck routes on Interstates and arterials. As well, the terminals provide points of contacts for surveys of terminal operators and truck operators on vehicle activity.

In late November, 1995, after the trees have lost foliage, aerial photography will be used to identify traffic volumes and the locations of truck activity. In addition, the research team is currently investigating the feasibility of using Russian satellite photography recently made available to the public. By overlapping the images, these data sources should allow vehicle classification counts to be made, and if resolution permits, may provide information on speed-acceleration profiles for the modeled network.

### Heavy-Duty Vehicle Load Factors

Weigh-in-motion equipment at Georgia weigh stations vary by age, manufacturer, and level of sophistication. Unfortunately, only two of the weigh stations in Georgia have the ability to save or print the data which are collected. One of these stations is located in Douglas County which is about 20 minutes west of Atlanta along I-20. This location is outside of Atlanta's perimeter freeway (I-285) and therefore captures a significant fraction of truck traffic skirting the city en-route to locations southeast of Atlanta.

The Douglas County weigh-in-motion equipment provide data on number of trucks, speed at which truck weights were measured, measurement location, date/time, whether a potential weight violation was identified, truck classification, total weight measured in kips (thousands of pounds), weight/axle, total axle spacing for the truck, and consecutive axle spacings: An example of the format of such output is shown below.

0121	22 MPH	Lane 1	13:26	07-01-1995	Viol: PZ	
5-axle semi	Total	1	2	3	4	5
Axle Wt (kips)	61.7	9.6	13.1	12.8	12.5	13.7
Spacing (ft)	55.3		14.2	4.4	31.5	5.2

Portions of two days of data (July 1 and 3, 1995) were downloaded from the Douglas County weigh station and analyzed. These data include measurements from approximately 1000 trucks over a data collection period of 10 hours. Figures 5 and 6 illustrate the distribution of vehicle weights from the Douglas County weigh station during the time period of about 10:00 AM to 3:00 PM for each of the two days.

The weight distributions of the truck activity seen in Figures 5 and 6 are disaggregated into four vehicle classes in Figures 7,8,9,10 and 11,12,13,14, respectively. The truck classes include 2-axle trucks, 3/4 axle trucks, 5-axle trucks, and 6+ axle trucks. Note the significant differences in both the weight groups and distribution shapes noted for the vehicle classes. Of particular interest from an emissions modeling perspective: 1) the 2-axle group represents significantly lower weight vehicles, and 2) the 5-axle group evidences a pronounced bi-modal distribution form.

Additional collection of vehicle weight data using portable weigh-in-motion (WIM) stations is currently being examined. The use of portable WIMs would allow the cross tabulation of truck weight characteristics with speed and acceleration data collected concurrently using laser rangefinders and vehicle classification using the JAMAR boards mentioned earlier. The Planning and Data Services Division of GDOT has been contacted and discussions on cooperative studies in this area are being pursued.

The relationships between vehicle payload status (the spectrum from full truckload to empty trailer) and measured vehicle weights can be undertaken through on-site terminal and weigh station surveys coupled with weigh-in-motion sampling. Relationships developed through these studies would likely be employed in the emission rate modeling regime once a goods movement model is developed for the region.

#### Heavy-Duty Vehicle Speed/Acceleration Profiles

The focus of speed/acceleration profile studies in the Atlanta region is on those activities and physical locations where power enrichment is suspected, such as ramp junctions, grades, weave areas, intersections, and freeway segments. Studies for automobiles have been undertaken in Atlanta using laser rangefinders (LRFs) to capture speed/acceleration profiles of individual vehicles (Breiwich, 1993). The geometric considerations of ramps on vehicle modal activity were also investigated by California Polytechnic State University, San Luis Obispo (Sullivan, 1993), through use of video tape analysis. The Cal Poly study showed that modal profiles are significantly affected by many geometric variables, including grade, curvature, length, and mainline traffic considerations. Additional data have been collected in Atlanta using video surveillance equipment as well, and this method is discussed elsewhere (Guensler, et al.; 1995).

#### Laser Rangefinders:

Operating profiles for individual vehicles can be illustrated in a frequency plot, representing the fraction of time that a vehicle spends in particular speed and acceleration combinations. The operating mode frequencies for the vehicle fleet are hypothesized to be a function of fleet and driver characteristics, traffic volumes and other operating parameters, as well as specific geometric parameters.

The goals of the most recent speed/acceleration profile studies are to determine whether the modal operating frequencies for trucks are different than those of the traffic stream as a whole, and to identify characteristic modal operating frequencies for various truck classes as a function of traffic and infrastructure parameters. Estimated truck modal

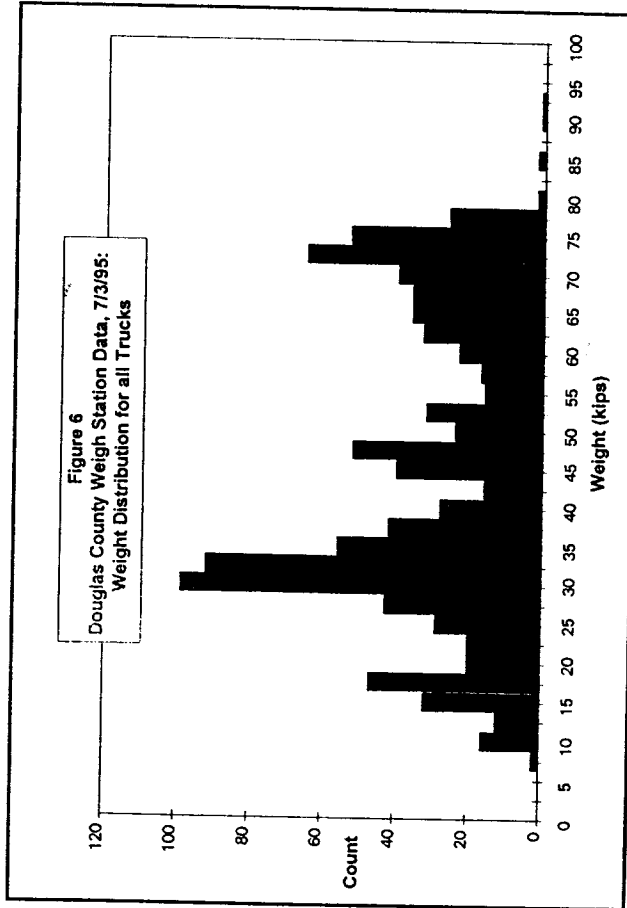
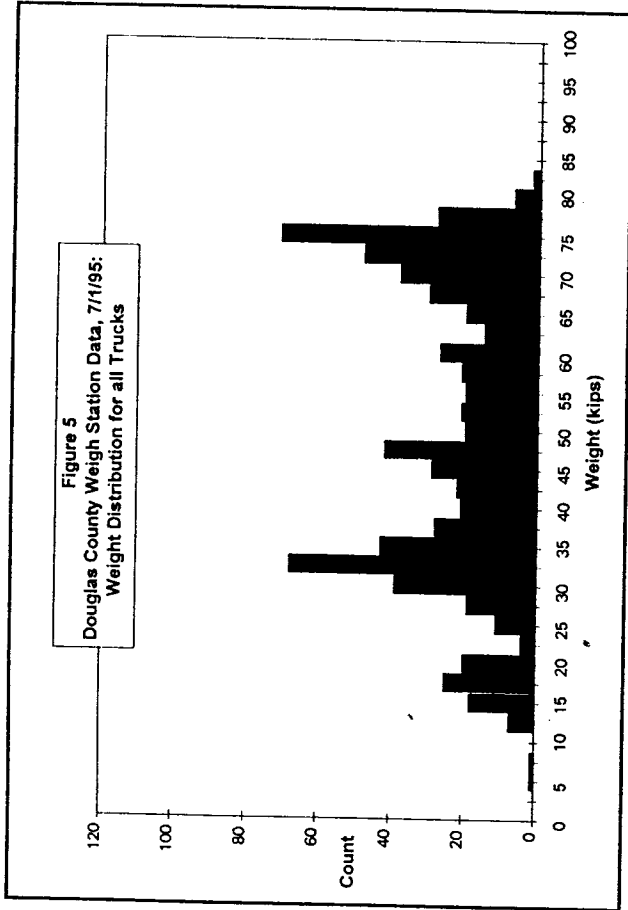


Figure 7  
Douglas County Weigh Station Data, 7/3/95: Weight Distribution for 2-  
axle SU Vehicles

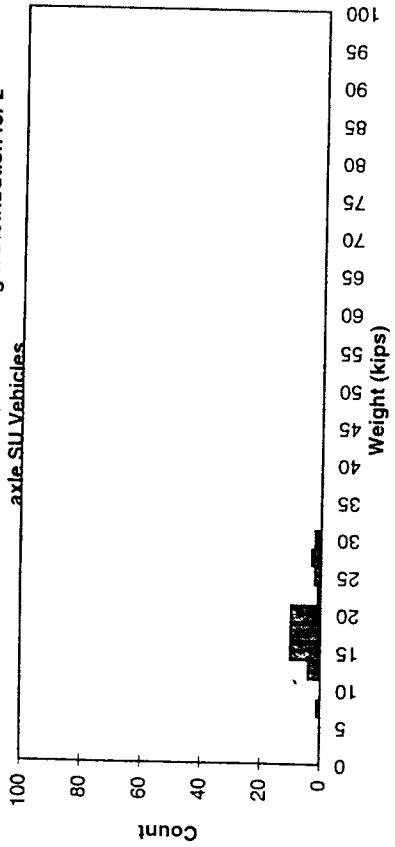


Figure 9  
Douglas County Weigh Station Data, 7/1/95: Weight Distribution for 3-4-  
ax Semi Vehicles

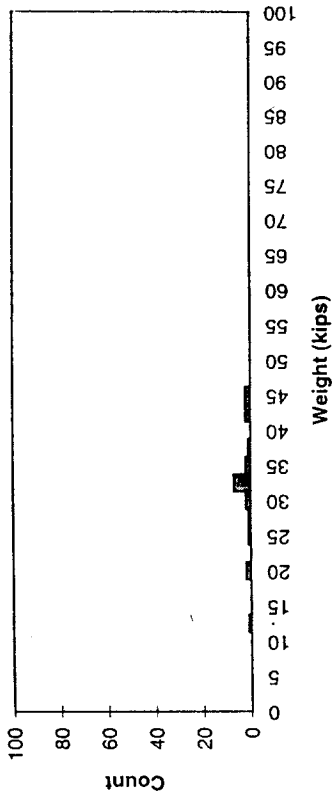


Figure 8  
Douglas County Weigh Station Data, 7/1/95: Weight Distribution for 3-  
axle SU Vehicles

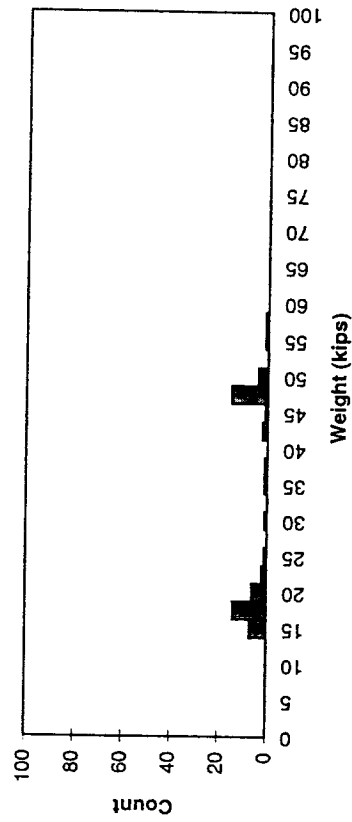
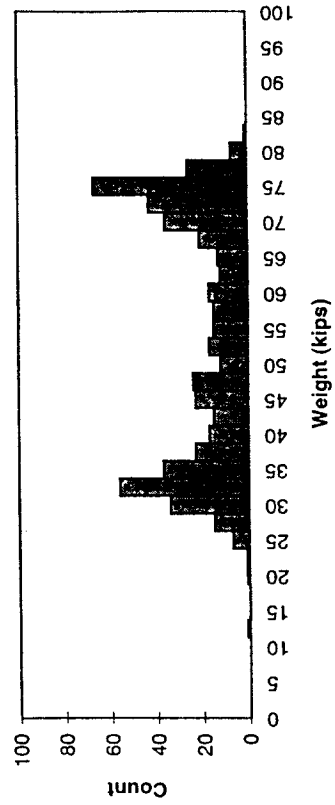
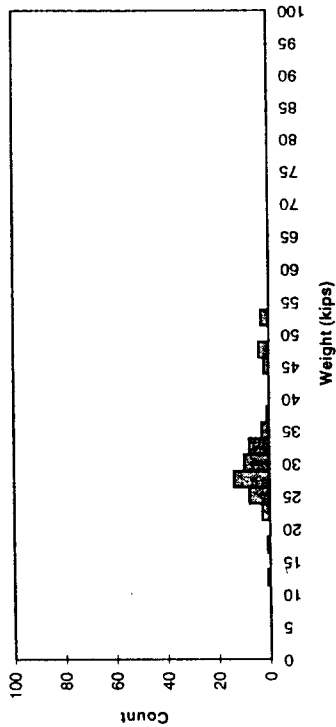


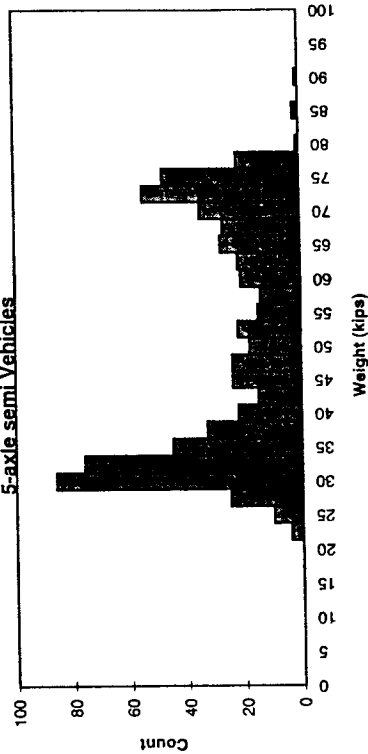
Figure 10  
Douglas County Weigh Station Data, 7/1/95: Weight Distribution for 5-  
axle semi Vehicles



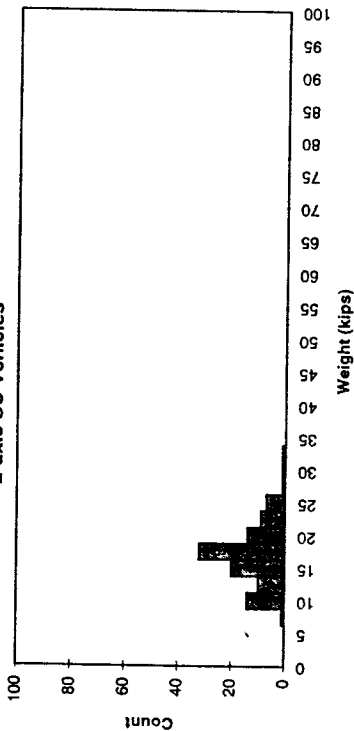
**Figure 13**  
 Douglas County Weigh Station Data, 7/3/95: Weight Distribution for  
 3-4-ax Semi Vehicles



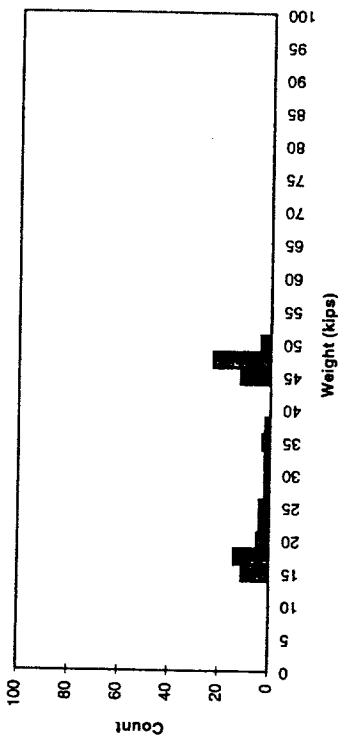
**Figure 14**  
 Douglas County Weigh Station Data, 7/1/95: Weight Distribution for  
 5-axle semi Vehicles



**Figure 11**  
 Douglas County Weigh Station Data, 7/3/95: Weight Distribution for  
 2-axle SU Vehicles



**Figure 12**  
 Douglas County Weigh Station Data, 7/3/95: Weight Distribution for  
 3-ax SU Vehicles



frequencies must comply with the framework of the Georgia Tech modal emissions model, such that even rare events that may produce significant emissions are captured in the data collection process. Omitting a small percentage of high speed or high acceleration operations can result in omission of a significant fraction of truck emissions. Statistical analyses will be undertaken to ensure that data accuracy and precision do not adversely affect the resulting modal frequencies.

The chief instrument currently employed in data collection for the purpose of developing speed and acceleration profiles for individual trucks is a laser rangefinder. Laser rangefinders (LRFs) use a laser beam to locate and "lock on" to vehicles, and record the vehicle's position throughout the time interval in which the vehicle is tracked. Two Advanced Lidar System ProSurvey 1000 LRFs, manufactured by Laser Atlanta Optics, are currently being utilized for the study. The rangefinder is powered by a rechargeable battery pack when operating in the field and also comes with a vehicle cigarette lighter adapter. Under continuous use a fully charged battery pack lasts about three hours.

To collect data in the field, a portable laptop PC is linked to the rangefinder via the RS-232 serial port. The raw data from the laser gun are downloaded directly to the computer and is captured by native software, which supports read and write memory, limited LRF remote operation, and real-time display of range and speed information. To allow for post-processing, all commands and data capture are logged to a file.

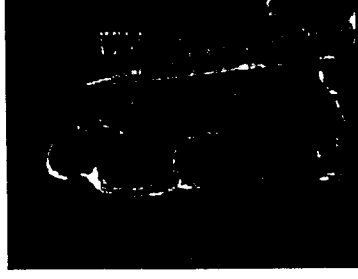
The LRF has three main modes of operation which are applicable to this study. In all three modes, the LRF is taking approximately 239 "shots" per minute which are used by an internal algorithm to compute either the range or the speed, depending on the mode of operation: speed mode, real-time ranging mode, and range averaging mode. For reasons discussed elsewhere (Guenstler, et al., 1995), the range averaging mode was selected for field studies.

To collect useful data using the LRF, the sights must be aimed at a solid metal portion of a vehicle, whether it be in the front or the rear. This requires that the LRF be continuously aimed at an appropriate part of the vehicle or data will be lost or corrupted. To facilitate the LRF data collection a surveying tripod mounted with a specially fitted bracket is utilized (see Figure 15). The study equipment needed for a single data collection station in the field includes: portable computer running LAEEPROM software, RS-232 serial cable, Laser Rangefinder, battery pack, surveying tripod with appropriate bracket, hand held tape recorder, and a double AA battery-powered JAMAR electronic counting board with an FHWA Type F classification template.

For mainline freeway segments, the recommended position for the LRF is on a bridge directly overlooking the lane of travel that is to be used to collect data. Vehicles are tracked by the LRF as they emerge from underneath the bridge and travel away from the study site. This is preferred to tracking the vehicles as they approach the site, as the most difficult part of tracking a vehicle is the initial "locking on" phase which is more easily accomplished when the vehicle is closer to the study area and the LRF. To best recognize and distinguish between vehicle types, it is essential that the number of vehicle units and number of axles can be counted. For this reason the recommended position of the person conducting the classification count using the JAMAR counting board is off to

the side of the bridge, so that the person is looking down at and almost perpendicular to the lane of travel being counted.

Figure 15: Laser Rangefinder Setup



The tracking of vehicles, using the LRF, is extremely restricted by line of sight, as seen through the recticle of the heads of display of the unit. Fixed objects such as road signs, light posts, trees, and even other vehicles in the roadway, especially trucks, can cause the LRF to produce false readings if vehicles are not carefully tracked and line of sight is blocked. If these objects are extremely close and are "shot" with the LRF, often an error message will be produced indicating a bad data stream and will cause LAEEPROM to log off. This requires that a new log file be created and the LRF must be remotely restarted. Ramp site locations are also severely limited due to safety considerations. The majority of bridges that overpass the Interstate 75/85 connector, running through the center of Atlanta, have wire fencing on the sides of the bridges. This at first seemed to eliminate these sites from consideration, but upon testing the LRF at two sites with such fencing the team discovered that careful equipment setup and use of the tripod eliminated line of sight problems.

Another important aspect of operating the LRF is the distance at which a vehicle is shot. The closer the vehicle under consideration is to the LRF unit, the more accurate the data. This is the primary reason for capturing vehicles as they depart from the site or overpass, rather than as they enter the field of view and approach the study site. Although the LRF is designed to function at ranges of up to 3500 feet, at this distance vehicles are indistinguishable. An initial estimate of the maximum distance at which the LRF will "lock on" to a truck is 2000 feet. Related to this is a third LRF operating consideration; more accurate readings are obtained from vehicles with larger rear metal areas. The LRF will not return a valid shot when aimed at the glass area of a vehicle. This is the major reason (aside from size) that trucks are much easier to track than passenger cars, and yield better data. Passenger cars frequently were unable to be tracked long enough to provide a sustained stream of data suitable for post-processing.



Initial site inspections have indicated that the beginning of an on-ramp is suitable for tracking truck activity as the vehicle travels towards the interstate. Equipment setups are successfully recording truck activity along "diamond" interchange ramp configurations. Site locations for Interstate locations are numerous in the Atlanta area, and can therefore be selected based solely on the characteristics of the freeway segment such as level of service, volumes, location, geometry, and percentage of trucks.

Data from 75 minutes of freeway onramp operation at I-285 and Bankhead Highway are presented in Figure 16. The same data were used to create Figure 17, which translates the observation frequencies into a shaded chart.

Figure 16  
On-Ramp Truck Activity, I-285 and Bankhead Highway

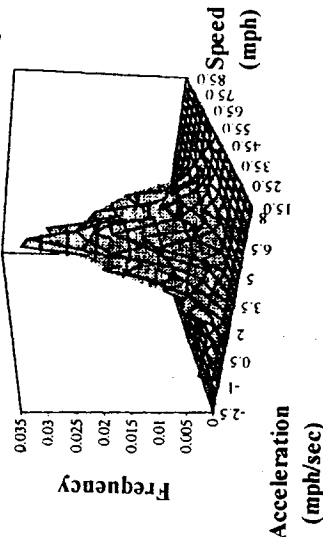
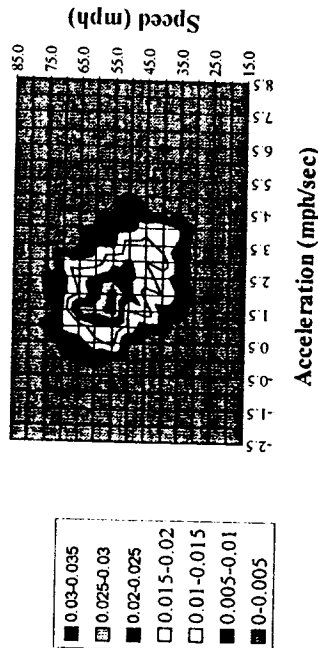


Figure 17  
On-Ramp Truck Activity, I-285 and Bankhead Highway



To correlate the speed and acceleration data captured for individual vehicles with other operating characteristics of those vehicles and the traffic stream characteristics at the time the LRF data are collected, vehicle classification counts on the JAMAR boards

can be correlated with the concurrent LRF data. Aside from providing a truck activity inventory for a given roadway segment, the classification counts also provide the opportunity to relate the speed and acceleration of an individual vehicle to the traffic stream composition.

## CONCLUSION

The initial results of the various heavy-duty vehicle studies are promising. The data necessary for more accurate estimates of truck activity can be successfully collected. The laser rangefinders have successfully yielded speed/acceleration profiles along a specific freeway onramp. The portability of the laser rangefinder and the JAMAR boards will allow data to be collected in many different areas so that a representative sample of speed/acceleration profiles and vehicle classifications can be assured. Numerous weigh-in-motion scales operated by different agencies throughout Georgia will provide spatial and temporal distributions of truck weights as well as additional vehicle classification data. Operations and maintenance records from private truck companies have the potential to link engine characteristics and truck weights to vehicle classification data. The option of using a portable weigh-in-motion scale provides an opportunity to have all necessary truck activity data collected from a single sample.

There is still a large amount of data collection which must be performed for each of the necessary data categories: vehicle classification, truck weight distribution, and speed/acceleration profiles. A major task also remains to link vehicle classification data with specific engine horsepower characteristics. Future studies and the continuance of data collection efforts already initiated will provide more detailed data. Statistical analysis will be required in all of these research areas to ensure that samples are representative and that cause-effect relationships are appropriately modeled.

## REFERENCES

- Brewish, R. "Road Network Behavior Characteristics as They Relate to Mobile Emissions: An Investigation of Power Enrichment"; Thesis submitted as Partial Requirement of Ph.D. Degree; Georgia Institute of Technology; Atlanta, GA; August 1993.
- Guenster, R., D. Sperlring, and P. P. Jovanis, "Uncertainty in the Emission Inventory for Heavy-Duty Diesel Powered Trucks (UCD-ITS-RR-91-02). Institute of Transportation Studies. University of California, Davis. Davis, CA. 1991.
- Guenster, R., D. Sperlring, and P. P. Jovanis. "A Research Plan Designed to Reduce Uncertainty in the Emission Inventory for Heavy-Duty Diesel-Powered Trucks (UCD-

- ITS-RR-92-01)". Institute of Transportation Studies. University of California, Davis, Davis, CA. January 1992.
- Nelson, C., S. Siwek, R. Guensler, and K. Michelson. "Managing Trucks for Air Quality: Current Work in Progress". Transportation Research Record. Number 1312. pp. 50-58. Transportation Research Board. Washington, DC. 1991.
- Ostria, S. "Estimating the Emissions Contribution of Intercity Freight Transport". Draft Paper for Presentation at the 1996 Annual Meeting of the Transportation Research Board. January 1996
- Sullivan, E., and Chatzioanou, A. "Vehicle Speeds and Accelerations along On-Ramps: Inputs to Determine the Emission Effects of Ramp Metering". California Polytechnic State University, San Luis Obispo, October, 1993.