HEAVY-DUTY VEHICLE WEIGHT AND HORSEPOWER DISTRIBUTIONS: MEASUREMENT OF CLASS-SPECIFIC TEMPORAL AND SPATIAL VARIABILITY

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HEAVY-DUTY VEHICLE WEIGHT AND HORSEPOWER DISTRIBUTIONS:

MEASUREMENT OF CLASS-SPECIFIC TEMPORAL AND SPATIAL VARIABILITY

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GLOSSARY / ACRONYMS

CAA, Clean Air Act

CAAA, Clean Air Act Amendment (of 1990)

CO, Carbon Monoxide

DOT, Department of Transportation

EPA, Environmental Protection Agency

FET, Fuel Economy Test

FTP, Federal Test Procedure: The test procedure as described in 40 CFR 86.130-00 which is designed to measure urban driving tailpipe exhaust and evaporative emissions over the Urban Dynamometer Driving Schedule as described in 40 CFR part 86 appendix I.

FHWA, Federal Highway Administration

GAO, General Accounting Office

GDOT, Georgia Department of Transportation

GIS, Geographic Information System: A computer hardware/software combination which is capable of integrating and graphically displaying spatial and temporal information.

GVW, Gross Vehicle Weight, The total weight of a vehicle which includes tractor, trailers, and all goods.

GVWR, Gross Vehicle Weight Rating, The total weight for which a particular vehicle is designed.

HDV, Heavy-Duty Vehicle: Any motor vehicle rated at more than 8,500 pounds GVWR or that has a vehicle curb weight of more than 6,000 pounds or that has more than 2 axles.

HP, horsepower.

HPMS, Highway Performance Monitoring System, A federally-mandated data collection effort that counts, classifies, and weighs vehicles through the national road infrastructure.

Kip, measuring unit, equal to 1,000 pounds

LDV, Light-Duty Vehicle: A passenger car derivative capable of seating 12 passengers or less.

MEASURE, Mobile Emissions Assessment System for Urban and Regional Evaluation. The modal emissions model developed at Georgia Tech and the model in which the weight and horsepower distribution models developed in this thesis will be incorporated.

MPS, Manual Peak Shifting: The post-processing method applied to the raw weight data from the portable weigh-in-motion equipment

NO_2, nitrogen dioxide

NO_x, nitrogen oxides

PM, Particulate Matter, includes solid particles and liquid droplets (non H_2O)

PM_{10}, Particulate Matter with a diameter of less than 10 microns

PWIM, Portable Weigh-In-Motion: WIM technology that can be transported between different locations.

UMTRI, the University of Michigan Transportation Research Institute

WIM, Weigh-In-Motion: a technique for collecting the weight of a vehicle without stopping the vehicle

SUMMARY

Planners and decision-makers use transportation and emission models to determine local conformity with air quality regulations. For heavy-duty vehicles, emission rates are highly correlated with engine load, which in turn is a function of vehicle weight, road grade, and onroad vehicle operations. Load-based emission models are currently being developed by the USEPA and other universities at the national level for various classes of heavy-duty vehicle engine technology. However, current onroad data for engine technology class and heavy-duty vehicle weights are inadequate to link with these new models (due to non-representative samples included in truck surveys and the predominance of non-urban weigh-in-motion sites). Therefore, the heavy-duty portion of emission models requires new input data to properly integrate with current transportation models.

The goal of this research is to develop a procedure for collecting heavy-duty vehicle weight and horsepower data and to develop models that will predict the percentage of activity for various temporal and spatial conditions in a metropolitan area. Portable weigh-in-motion equipment, State of Georgia weigh station data, and roadside truck surveys are used to collect data for the onroad heavy-duty vehicle fleet. This research statistically measures the interaction between heavy-duty vehicle class, weight and horsepower distributions. The application of these results will improve heavy-duty emission models by allowing for temporally and spatially disaggregated heavy-duty vehicle data inputs to generate more accurate emissions estimates.

CHAPTER I

1. INTRODUCTION

Current regulatory emission rate models utilize highly aggregated vehicle characteristics and activity parameters that do not represent the full range of heavy-duty vehicle operations. Recent research suggests that through modeling emissions for light-duty vehicles from specific modes of vehicle operation and replacing the current driving cycle with operating mode distributions, the level of aggregation is reduced (Barth, 1997; Guensler, 1996). For the purposes of emission estimation, heavy-duty vehicles are classified by engine technologies, and for each engine technology category, emission rates are thought to be constant on a gram per brake-horsepower-hour basis with some deviations during extreme conditions. Engine horsepower is the most common engine technology used in emission rate modeling. Several research teams are currently developing improved heavy-duty vehicle emission rates including the Environmental Protection Agency (EPA), the California Air Resources Board (CARB), West Virginia University, and the Desert Research Institute (DRI).

Georgia Tech's MEASURE model combines modal emission rates with onroad engine and modal operations to predict emissions as a function of engine load for light-duty vehicle technologies. Heavy-duty vehicle emission rates are modeled as a function of instantaneous engine load, which is related to factors such as vehicle weight, road grade, and onroad vehicle operations. However, current onroad data for engine technology class and heavy-duty vehicle weights are inadequate to link with these new models due to non-representative fleets included in truck surveys (Lau, 1991) and the lack of quantifiable accuracy of weigh-in-motion devices (Dahlin, 1992). Therefore, the heavy-duty portion of the modal emissions model requires new input data to properly integrate with current transportation models.

This research focuses on three heavy-duty vehicle data inputs to emissions models: vehicle classification, vehicle weights, and vehicle horsepower. The data collected in this research bridge the gap between the current truck activity data that are categorized by truck classification and the ongoing engine emission rate studies that are categorized by engine technology. A single vehicle classification will be developed which can be used to generate heavy-duty vehicle horsepower and weight distributions.

1.1 Heavy-Duty Vehicle Classification Systems

Current heavy-duty vehicle classification methods do not match with onroad vehicle activity and characteristics categories. Most emissions-related heavy-duty vehicle classifications are based upon gross vehicle weight rating as a result of the availability of accessing this data from vehicle registration databases. These ratings are based on the maximum weight that a vehicle can carry relative to the horsepower capacity and safety considerations of the vehicle. However, as engine technology continues to improve, the horsepower of all classes of heavy-duty engines has increased, thereby allowing for gross vehicle weight ratings well beyond the onroad weights actually experienced by many vehicles.

Many heavy-duty vehicles are classified with the same weight rating despite having different onroad activity, weight, and horsepower characteristics. For example, a vehicle with a gross vehicle weight rating of 80,000 pounds can be either a 5-axle, long-haul, tractor-trailer combination with a 600 horsepower engine used for dry goods shipment or a 3-axle, local, single-unit vehicle with a 350 horsepower engine used for hauling loose materials. The onroad weight distribution of the 5-axle vehicle would range from an empty weight of 35,000 pounds up to the legal maximum of 80,000 pounds. The onroad weight distribution of 3-axle vehicles generally ranges from an empty weight of 20,000 pounds up to the legal maximum of 48,000 pounds. In a vehicle classification system based on gross vehicle weight rating these two vehicles would be classified in the same vehicle category despite the large differences in activity, weight range, and horsepower. The development of a classification scheme that more accurately reflects activity and vehicle characteristic differences of the heavy-duty vehicle fleet is needed to develop disaggregated data for modal emissions models.

1.2 Heavy-Duty Vehicle Weight Data Collection

Truck weight data are critical inputs for load-based heavy-duty vehicle emissions models. These data are currently collected by state transportation agencies to assist in pavement design processes and pavement management. However, much of the weight data have questionable accuracy due to inadequacies of the equipment and insufficient equipment calibration methods.

A comprehensive calibration method for portable weigh-in-motion equipment used in conjunction with temporary loops and sensors has not yet been developed. The traditional method of calibrating weigh-in-motion sites is through the use of a single test truck at a single weight. This method has several problems. Most notably, research suggests that the dynamics of any specific truck are very unique and can be different from other trucks even those of the same vehicle classification (Dahlin, 1992). Alternative methods have been developed to calibrate WIM equipment, but the methods vary with the type of WIM equipment used and the type of vehicle classification of concern for the weight data collection effort (Wu, 1996; Papagiannakis et al., 1996; Dahlin, 1992; Fekpe et al., 1992; ASTM 1994).

Data sources for heavy-duty vehicle weights are currently not representative of metropolitan level activity. Current permanent sites used for collecting vehicle weight data have been selected based on statewide pavement monitoring and weight enforcement needs. Many of the sites are focused on bridges that are structurally sensitive to vehicle weight. Other sites are located on the rural portion of freeways in order to capture a large quantity of intercity truck trips that are believed to include a relatively high percentage of heavily-loaded vehicles. Therefore, much of the weight data collected by state agencies is incompatible with the data needs of metropolitan level emissions models. New vehicle weight data need to be collected which focuses on temporal and spatial representation of metropolitan level heavy-duty vehicle activity.

1.3 Heavy-Duty Vehicle Horsepower Data Collection

Current onroad heavy-duty engine technology class data are inadequate to link with the emerging load-based emission models. The EPA has currently defined heavy-duty engine technology according to horsepower, but non-representative samples of trucks included in current survey methodologies are inadequate for predicting the onroad horsepower distribution. National and state level truck surveys do not include horsepower as a data item in the survey instrument. Current metropolitan-level commercial vehicle surveys are not representative of onroad truck fleets as a result of the large percentage of trucks operating in an urban area that are registered outside of that area. Trucks registered outside of the metropolitan area are generally not included in the sample framework for commercial vehicle surveys. The data collected in this research will include horsepower from roadside truck surveys. This inclusion represents a significant improvement over the current paucity of onroad engine horsepower data.

1.4 Research Approach

This research began with the development of an approach to collect spatially representative truck weight and horsepower data throughout the Atlanta metropolitan region.

Roadside truck surveys were implemented at several locations to link weight data with horsepower data, and to generate spatially representative horsepower distributions. Horsepower bins were developed through grouping broad categories of operational characteristics based on conversations with truck manufacturers.

Portable weigh-in-motion devices along with temporary loops and sensors, currently used by many state transportation agencies, were determined to be instruments that could collect class-specific truck weight data without requiring continual manual oversight. Relevant weight bins were determined for each classification of vehicles based on vehicle characteristics, truck weight limits, and preliminary weight distribution characteristics. Time periods were determined from variability of preliminary weight distributions. The final models include the frequency of trucks for each class in a particular weight bin for each relevant time period.

In this research, variability in heavy-duty vehicle weight and horsepower distributions is hypothesized to be a function of temporal characteristics and axle-trailer configuration. Heavy-duty vehicle weight distributions are hypothesized to be constant for a given time-of-day and day-of-week period based on preliminary results from Georgia weigh station data.

Axle-trailer configuration is a useful variable because it provides a classification format that is compatible with weigh-in-motion equipment data and is easily recognizable for conducting truck surveys. Additionally, vehicles with a particular axle-trailer configuration have weight characteristics in common. The empty weight of the vehicles of a particular configuration is similar as a result of similar vehicle design specifications. The full weight of vehicles of a particular configuration is uniformly restricted based on truck weight limits.

Truck weight and horsepower distributions are assumed to be constant over different spatial conditions, and this assumption is checked through the collection of data at numerous locations. The variability between weight distributions across a metropolitan area has been shown to be negligible in some limited studies (Blower and Pettos, 1988; Wegman et al, 1995).

The wide range of heavy-duty vehicle traffic in a metropolitan area also limits one industry or commodity type from dominating the overall goods movement of the local Interstate System.

The goal of this research is to develop a procedure for collecting truck weight and horsepower data and to generate models that will predict the percentage of activity for a range of temporal conditions in a metropolitan area. Through the use of portable weigh-in-motion equipment, weigh station data, and truck surveys, weight data were collected on over 75,000 heavy-duty vehicles and horsepower data were collected on over 400 heavy-duty vehicles. The research measured the interaction between heavy-duty vehicle weight and horsepower distributions and generated truck-class-specific estimates for horsepower and weight distributions. The application of these results will improve heavy-duty modal emissions modeling by allowing for temporally and spatially disaggregated data inputs to generate more accurate emissions estimates.

1.5 Summary of Contributions to Heavy-Duty Vehicle Modeling

There are four major contributions developed by this research. First, a heavy-duty vehicle classification format suitable for describing both horsepower and weight distributions is established. This classification format will allow for data from numerous truck data sources (i.e. roadside surveys, vehicle counts, emission rate estimates, commercial vehicle surveys, etc.) to be easily incorporated into emissions models.

Second, the relationship between horsepower and weight is examined to determine if there is matching of heavy loads to higher horsepower engines by truck dispatchers. This relationship will determine the extent of the independence of horsepower and weight for the final models produced in this research. Third, the horsepower distributions will be developed for the onroad truck fleet and examined for spatial variability. Finally, weight distributions will be developed that describe the temporal fluctuations of each truck classification in the onroad truck fleet. The weight distributions will also be examined for spatial variability.

CHAPTER II

2. BACKGROUND ON HEAVY-DUTY VEHICLE ACTIVITY

Heavy-duty vehicles can range from small 10,000 pound, 2-axle vehicles with less than 200 horsepower to large tractor-trailer combinations with 5 or more axles hauling 80,000 pounds with a 500 horsepower engine. This wide range in heavy-duty vehicle characteristics has developed over time to serve different categories of goods movement while satisfying the federal and state heavy-duty vehicle regulations. Understanding the range of heavy-duty vehicle activity and operating characteristics is important in developing a heavy-duty vehicle weight and horsepower model. This chapter defines important heavy-duty vehicle activity generators, truck terminology, and regulations; followed by an examination of the physical forces which work to prevent vehicle motion; and concluding with the diesel engine horsepower and transmission designs developed to overcome these resistance forces.

2.1 Heavy-Duty Vehicle Activity Generators

A comprehensive guidebook for understanding the nature of freight transportation activities was published by the National Cooperative Highway Research Program (Cambridge Systematics, 1997). This guidebook includes a list of the factors that influence freight demand including the industrial location patterns, economic deregulation, and local infrastructure system. This section describes how these factors influence truck activity and specifically the truck class, weight, and horsepower characteristics of interest in this research.

2.1.1 Industrial Location Patterns

The spatial distribution of economic activities determines the specific transportation mode, timing of freight shipments, and vehicle flows. To develop a model with local specifications of spatial and temporal truck classification, the spatial distribution of economic activities must be considered. Mode choice for freight transportation depends on a number of factors including the distance shipped, perishability of the good, and modes available at the origin and destination.

The location and type of industrial activity also affects the classification of heavy-duty vehicles used for goods movement. Goods produced from factories often necessitate long-haul trucking which travel primarily from factories to warehouses, as opposed to regional trucks that travel primarily from warehouses to other warehouses and end users. A 1985 survey by the Port of New York and New Jersey found that different types of trips and trip lengths resulted in different truck fleet mixes. This study found that almost 90% of the through trucks in the New York metropolitan area were large vehicles, while only 45% of the regional trucks were categorized as large (Strauss-Wieder, 1987). Similar results have been found in other truck surveys as explained later in this section.

The importance of industrial location to commodity type has led to the theory that there may be a relationship between spatial attributes and gross vehicle weight distribution within specific truck classifications. This relationship would be valid if weight distributions were shown to vary by commodity type and industrial activity varied significantly throughout a metropolitan region. Unfortunately, the research in this area has been limited. To date, there has been limited study of the relationship between vehicle weight and cargo type. One research project developed a disaggregate file of commodity attributes which related the commodity types with the density of the natural resource shipments (Kuttner, 1979). This data can be used to develop theoretical vehicle weight data based on assumptions about vehicle size, mode choice, and packaging materials. There are few historic estimates of shipment densities or on how the shipment densities have changed over time.

2.1.2 Economic Deregulation

A significant amount of deregulation occurred during the 1970s and early 1980s. The culmination of this deregulation included passage of the following legislative acts: the Airline Deregulation Act of 1978, the Motor Carrier Act of 1980, the Staggers Rail Act of 1980, and the Shipping Act of 1984. Deregulation of the airline, rail, and water transport industries has resulted in the vertical integration of freight services by creating a highly competitive market characterized by high reliability, endpoint pickup and delivery, and a wide array of cost and service options.

The Motor Carrier Act of 1980 eased the entry of new truck companies into new and expanding markets by making it more difficult for existing carriers to block truck companies from expanding on previously restricted routes. To meet the needs of customers, these new truck companies created a wide variety of shipping options. Large truckload carriers developed new operating strategies such as hiring their own drivers, purchasing equipment in bulk at large discounts, increasing the focus on corridors with medium to high densities of demand, and the development of directionally balanced shipping routes. Deregulation also facilitated the incorporation of just-in-time shipping practices and centralized warehouses which increased the volume of truck activity while decreasing the percentage of full shipments on the roadways. Deregulation has led to a much more complex trucking industry with an increased amount of companies some with very narrow market niches and others that are general shippers carrying a wide range of products on several types of facilities. Generating weight and horsepower distributions in a deregulated market requires increased sampling to capture a representative portion of the truck fleet.

2.1.3 Local Road Infrastructure

The configuration of the road network (in addition to specific truck route restrictions) has significant implications for truck route choice and will also influence location decisions for truck intermodal facilities and break-bulk operations. The presence and severity of congestion in large urban areas will also effect intercity traffic as long-haul trucks attempt to avoid congested areas during peak vehicle volume hours. Congestion also impacts intra-city trucking through route choice and timing of pickups and deliveries throughout a metropolitan area.

Highway tolls and other user fees can divert truck traffic away from expensive routes or attract truck traffic if the toll reduces congestion caused by passenger car traffic. The existence of weight enforcement stations can also alter truck routes. Weigh station avoidance occurs by overweight heavy-duty vehicles to avoid paying the fine for exceeding legal truck weights (Cunagin, 1997). Even heavy-duty vehicles that are under the legal limits may choose routes to avoid weigh stations to avoid potential delays at these locations.

2.2 Heavy-Duty Vehicle Classification

2.2.1 Trucks, Tractors, and Trailers

The terms trucks, tractors, trailers, and semis are often used improperly due to the combination of technical and layman use of each of these terms. The term “truck” technically refers to a vehicle designed for carrying the entire weight and bulk of a load. For single-unit heavy-duty vehicles, the entire vehicle is invariably referred to as a truck. However, heavy-duty vehicles with multiple units (often referred to as combination vehicles) are technically not trucks. These are tractors with one or more trailers, even though they are commonly referred to as trucks or semis even by their drivers. A tractor is defined as a vehicle designed for pulling loads greater than the weight actually applied to the vehicle. The trailer on which the load is carried is generally connected to the tractor through the use of a fifth wheel. To avoid confusion between the technical and common terms for trucks, tractors, and semis, the term heavy-duty vehicles (HDVs) is often used in technical fields to include non-light-duty trucks, tractors, and tractor-trailer combination vehicles. However, due to the common usage of the word truck in general items related to this research (i.e. truck company, truck size and weight limits, truck drivers, etc.), the term truck is often used interchangeably with heavy-duty vehicle in this dissertation.

2.2.2 Vehicle Classification Schemes

Two primary classification methods are used to separate heavy-duty vehicles from the other vehicle classifications within the overall fleet and to subdivide the heavy-duty vehicle fleet: axle/trailer configuration and gross vehicle weight rating. The specific classification scheme utilized depends on a combination of factors including the data collection device, the purpose of the classification scheme, and the overall vehicle mix being classified. Each classification scheme has distinct advantages and disadvantages.

2.2.2.1 Gross Vehicle Weight Rating Classification Schemes.

Gross vehicle weight rating (GVWR) is the legal load capacity of a single heavy-duty vehicle. This rating is calculated by adding front and rear axle capacities, including suspension, wheel, tire, and brake limitations. The availability of vehicle registration data makes a GVWR method of classifying easy to implement for the purposes of calculating vehicle taxes and developing emissions regulations. The Environmental Protection Agency (EPA) uses a GVWR scheme, featuring two light-duty truck (LDT) classes and three heavy-duty diesel engine (HDDE) vehicle classes, to distinguish vehicles for the development of emissions standards (Figure 2-1). Use of GVWR to classify vehicles can be problematic because vehicles with the same weight rating are often used in very different fashions. In addition, a particular vehicle, such as a utility vehicle, can be used for multiple purposes such as commuting, hauling goods, or recreational purposes that are completely unrelated to the GVWR of the vehicle.

Light-Duty Trucks (LDT): GVW<=8,500 lbs.	Light LDT: GVW<=6,000 lbs.
	Heavy LDT: GVW 6,001-8,500 lbs.
Heavy-Duty Vehicles (HDV): GVW>8,500 lbs.	Light HDDE: GVW 8,501-19,500 lbs.
	Medium HDDE: GVW 19,501-33,000 lbs.
	Heavy HDDE: GVW>33,000 lbs.

Figure 2-1: EPA GVWR Classification Scheme

2.2.2.2. Axle-Trailer Classification Schemes

Classification based on the number of axles and trailers is the simplest method for either automated or manual roadside count/classification programs and for roadside surveys. The Federal Highway Administration (FHWA) has created a standard 13-vehicle classification program which is often utilized by state DOTs in the administration of statewide count and classification programs (Figure 2-2, FHWA, 1994). The FHWA classification scheme features two classes that are always light-duty vehicles: motorcycles and passenger cars. The scheme also has nine classes which are always heavy-duty vehicles including buses and vehicles with 3 or more axles. However, classification #3 and classification #5 feature vehicles which can be either light or heavy-duty vehicles. Classification #3 includes pickups, vans, sport utility vehicles, and other long 2-axle, 4-tire vehicles; while classification #5 includes all 2-axle, 6-tire vehicles. In addition, the truck classifications from #5 to #8 can feature either light-duty, medium-duty, or heavy-duty diesel engines. Therefore, translating data collected from axle-trailer classes into GVWR classes is not always possible without very detailed information on each individual vehicle.

During manual vehicle classification and count programs, distinguishing between classes is generally based on body style differences between various vehicle types. The body style of a passenger van is easily distinguishable from a pickup truck. In addition, the majority of commercial vehicles are recognizable through the use of highly visible truck company names on the side of the truck enabling a simplified classification between passenger and freight-carrying commercial vehicles for most of the vehicle fleet. The data collection methods of this research involve manual and automated truck classification. Therefore, the classification schemes in this research are based on axle-trailer configurations as opposed to GVWR classes.

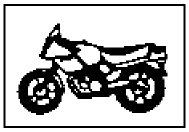


Figure 2-3(a), Classification #1, Motorcycles

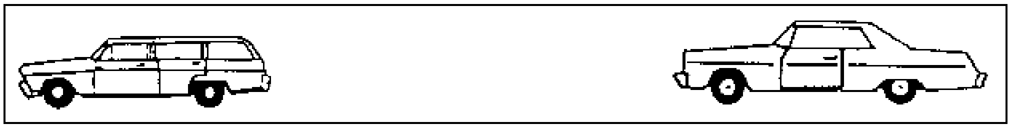


Figure 2-3(b), Classification #2, Passenger Cars

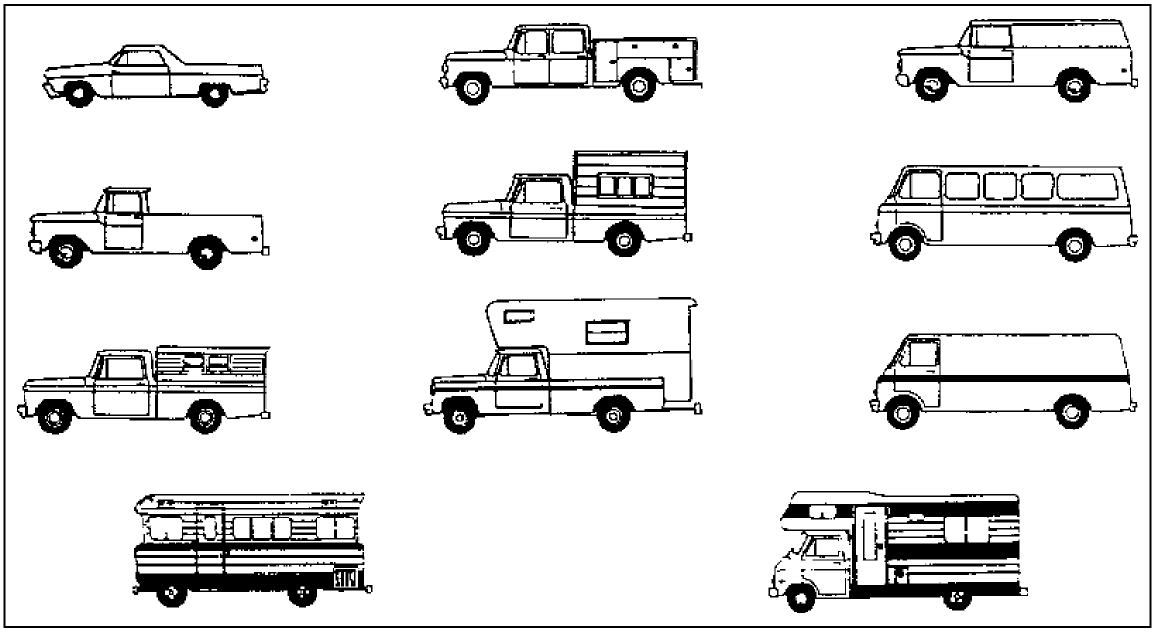


Figure 2-3(c), Classification #3, Pickups, Vans, Sport Utility Vehicles, and other 2-axle 4-tire vehicles

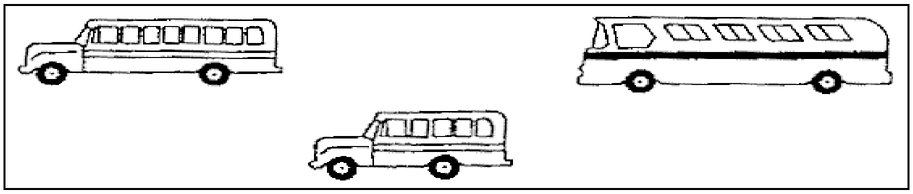


Figure 2-3(d), Classification #4, Buses

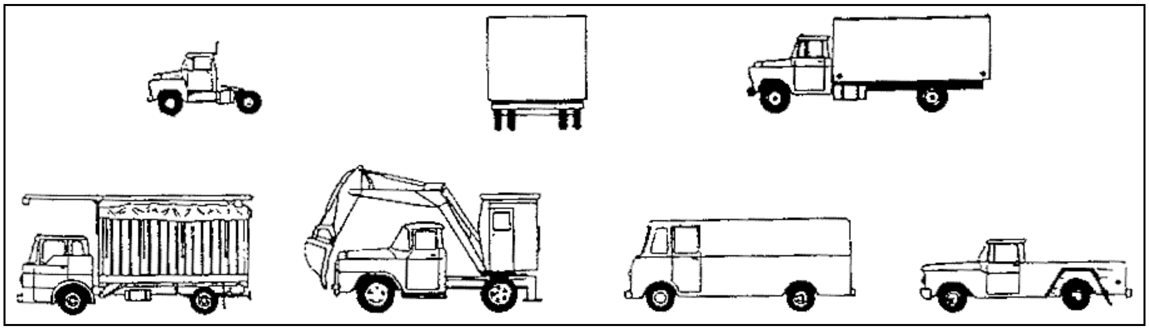


Figure 2-3(e), Classification #5, Two-axle, Six-tire Single Unit Trucks

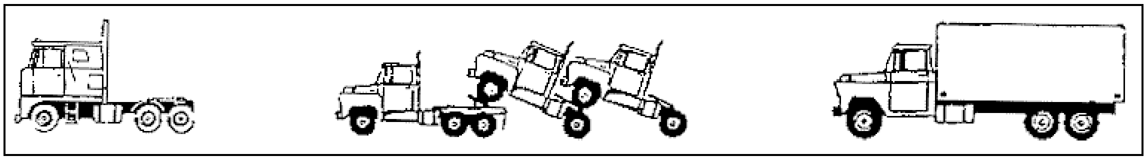


Figure 2-3(f), Classification #6, Three-axle Single Unit Trucks

Figure 2-3(g), Classification #7, Four or more axles, Single Unit Trucks

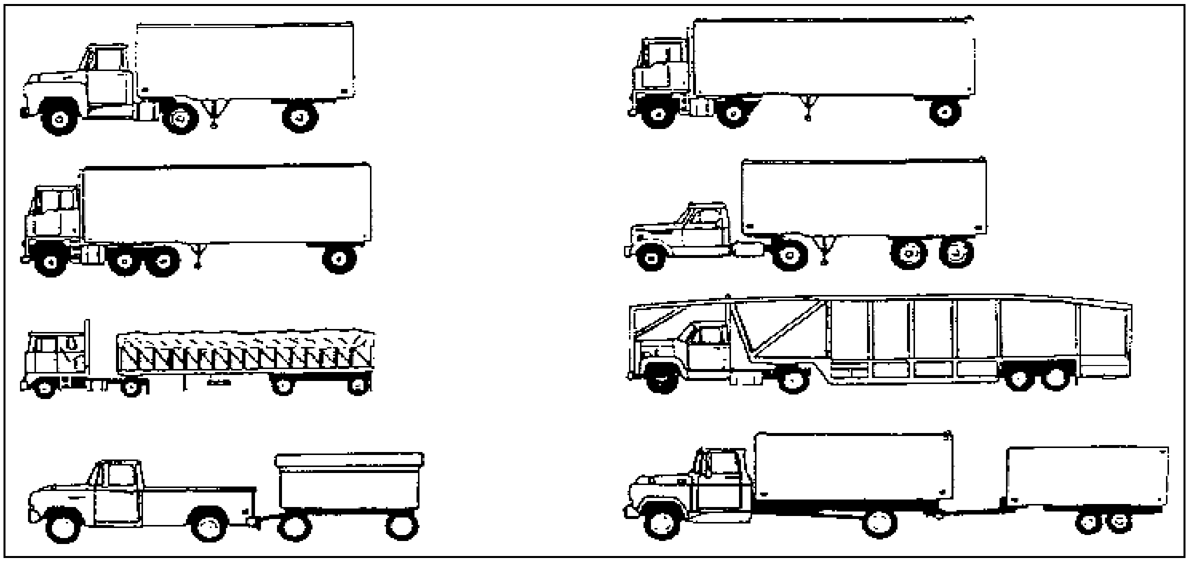


Figure 2-3(h), Classification #8, Four or less axles Single Trailer Truck Combination

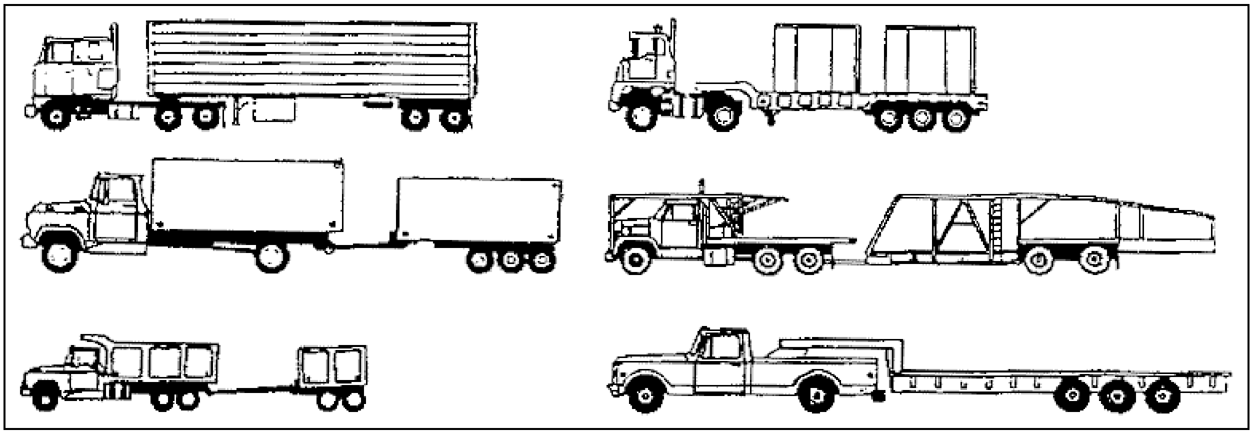


Figure 2-3(i), Classification #9, Five-axle Single Trailer Truck Combination

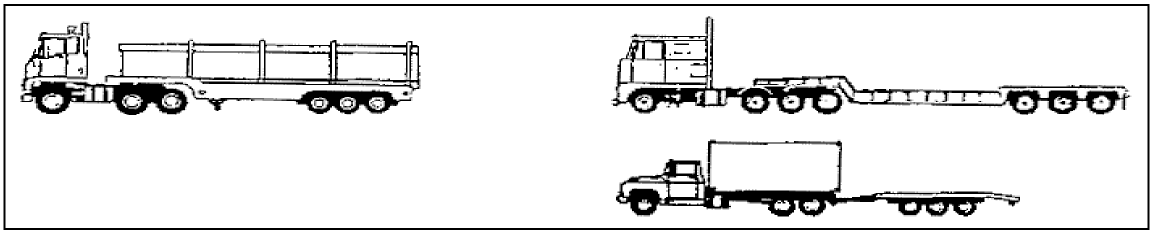


Figure 2-3(j), Classification #10, Six or more axles Single Trailer Truck Combination

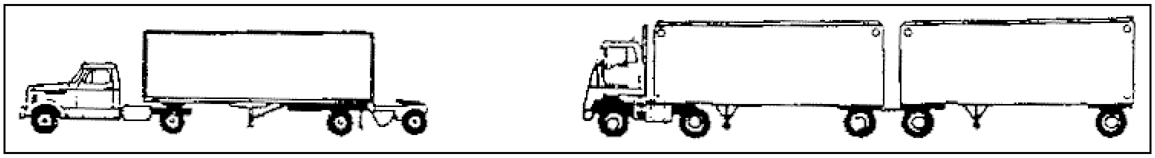


Figure 2-3(k), Classification #11, Five or less axles Multi-Trailer Truck Combination

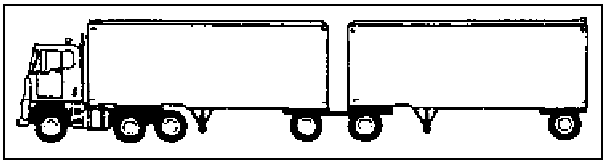


Figure 2-3(l), Classification #12, Six-axle Multi-Trailer Truck Combination

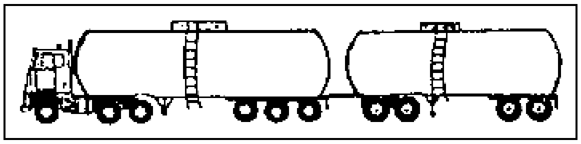


Figure 2-3(m), Classification #13, Seven or more axles Multi-Trailer Truck Combination

2.3 Truck Size and Weight Limits

Limits on vehicle size and weight play a significant role in the class and weight distributions of the heavy-duty vehicle fleet. The limitations on truck size and weight are designed primarily to regulate the amount of damage to roads that results due to the heavier weights of heavy-duty vehicles compared to passenger vehicles. The combined size and weight limits also serve as the basis for the design specifications of many aspects of heavy-duty vehicles including horsepower. For example, when federal gross vehicle weight limits (along with many state limits) were raised to 80,000 pounds, the horsepower designed into trucks used for intercity travel increased as well.

The implementation of truck weight limits takes the form of separate maximum allowable weights for individual axles, tandem axles, and entire vehicles depending on the axle-trailer configuration. There are federal limitations on truck size and weight which serve as the maximum allowable for Interstate trucks. Only seven states adopt the federal limitations in their entirety. As a result of the evolution of truck size and weight regulations (which includes the grandfathering of the limits in some states), many states have truck size and weight limits which are considerably below or above that allowed by the federal limits.

Federal truck weight laws apply to the Interstate System while Federal vehicle size law applies to the National Network (NN) which includes the Interstate System. Current Federal truck size and weight laws establish the following limits (FHWA, 1995):

- 20,000 pounds for single axles on the Interstate System;
- 34,000 pounds for tandem axles on the Interstate System;
- Application of Bridge Formula B, which limits the gross weight of any group of axles to the lesser of the tandem axle maximum or a value determined by the number of axles and the

distance between them, for other axle groups up to the maximum of 80,000 pounds GVW on the Interstate System;

- 102 inches for vehicle width on the NN;
- 48-foot (minimum) for semitrailers in a semitrailer combination on the NN; and
- 28-foot (minimum) for trailers in a twin-trailer combination on the NN.

Figure 2-3 shows the federal vehicle weight limits and the limits for a number of states in the southeast U.S. Similar to many states, Georgia allows for heavy-duty vehicle operators to purchase a permit to travel above the weight limit for the small fraction of truck shipments that require overweight transport. The typical permit is either for 100,000 pounds or 175,000 pounds for GVW, 23,000 pounds for a single axle, and 46,000 pounds for a tandem axle.

	Vehicle Weight Limits					
	Gross Vehicle		Single Axle		Tandem Axle	
Road Type	Interstate	State Hwys.	Interstate	State Hwys.	Interstate	State Hwys.
Federal	80,000	n/a	20,000	n/a	34,000	n/a
Georgia	80,000	80,000	20,340	20,340	34,000	37,340

Tennessee	80,000	84,000	20,000	20,000	34,000	40,000
Alabama	80,000	84,000	20,000	20,000	34,000	40,000
Florida	80,000	80,000	22,000	22,000	44,000	44,000
South Carolina	80,000	80,600	20,000	22,000	34,000	39,600
North Carolina	80,000	80,000	20,000	20,000	38,000	38,000

Figure 2-3: Federal and State of Georgia Truck Weight Limits

Vehicle size limitations can also affect the weight distribution of heavy-duty vehicles. Truck size limits regulate the length of the trailers that tractors carry, and the physical length of goods hauled. Therefore, goods that are shipped on a flat container are allowed to overhang the end of the trailer by a specified amount. Permits are allowed for shipments that require oversized transport such as mobile homes. Goods that are low in density can often result in vehicles that are full by volume, but not loaded to the legal weight limit. Vehicles loaded in this fashion will shift some of the weights within a particular vehicle class weight distribution from the legal maximum to a lower weight value.

Enforcement of the truck size and weight limits occurs primarily at state-operated weigh stations along the Interstate System. Many states with weigh stations located near borders with other states monitor the vehicle weights of trucks as they enter and exit the state. Weigh stations are generally operated by state highway patrol officers while being owned and funded by state DOTs. In Georgia, all weigh stations are operated through the use of a weigh-in-motion scale that screens vehicles based on an estimate of the individual axle, tandem axles, and gross vehicle weights. Vehicles whose weights are found to be near or exceeding any of the weight limits are electronically directed to the static scale where an exact weight measurement is taken. The reading from the static scale becomes the basis of issuing weight violations (in the form of fees) for overweight vehicles that are applied directly to the driver of the individual vehicle.

Efforts are underway to incorporate Intelligent Transportation System (ITS) technologies to improve vehicle flow at weigh stations. In Georgia, the Advantage I-75 program permits transponder-equipped trucks to travel any segment of the Interstate-75 corridor without reducing speeds while being cleared to bypass the weigh stations along the corridor (McCall, 1998). The evolution of electronic screening at weigh stations is an outgrowth of efforts to streamline and standardize motor carrier regulatory enforcement and may eventually lead to uniform weight regulations in regions throughout the nation.

Mobile inspection crews can also be used to set up temporary truck inspection stations using portable static scales. These mobile units are used primarily on state highways, and can only inspect a small number of vehicles per hour as opposed to the weigh stations that inspect all heavy-duty vehicles during periods of operation. Through the enforcement of truck weight limits and truck design specifications, there are strong incentives for Interstate vehicles to operate within the truck weight limits. This significantly affects the weight distribution of heavy-duty vehicles. Truck size and weight limits tend to increase with time as pavement technology continues to become more sophisticated in accommodating heavy vehicles and truck operators lobby to increase the limits to allow for the shipment of more goods using less resources.

2.4 Truck Operating Resistance Forces

Heavy-duty vehicles have incorporated a set of technologies that differ significantly from their light-duty counterparts to enable hauling of large loads at high speeds for long periods of time. Large engines with high horsepower are used in heavy-duty vehicles to provide sufficient towing capacity to counteract the forces resisting motion of trucks.

The horsepower of a heavy-duty vehicle engine is an important aspect of the truck or tractor's overall design. The engine horsepower determines the speed at which different weights can be hauled, the size characteristics of the engine, and the manufacturing cost of the power unit. For design purposes, the available power of a vehicle must equal or exceed the total of all resisting forces to maintain the desired speed for the load condition of the vehicle. The resisting forces include external tractive resistance forces and internal chassis resistance forces. The total tractive resistance, also known as running resistance, is the total of all external forces resisting the desired motion of the vehicle and includes the following three factors (Bosch, 1996):

- rolling resistance,
- aerodynamic drag, and
- grade resistance.

2.4.1 Rolling Resistance

The total force exerted by the tires of a vehicle on the road surface acting against the direction of movement is called rolling resistance. This resistance is the product of deformation processes which occur at the contact patch between tire and road surface. The force is generally calculated as a function of gross vehicle weight, speed, and surface adhesion. However, the surface adhesion is the result of numerous factors including the size of the tires, inflation pressure of the tires, tire wear, the temperature of the tires, and the type of pavement surface. Under normal operating conditions, the rolling resistance force equation takes the form:

$$F_{ro} = f * m * g$$

where

F_{ro} = rolling resistance force in N,

f = a constant based on surface adhesion,

m = gross vehicle weight in kg., and

g = gravitational acceleration in m/sec^2.

The rate of increase in rolling resistance with higher speeds is not as pronounced for heavier trucks and truck combinations as for lighter vehicles such as passenger cars due to the relatively low tire inflation pressure of heavy-duty trucks. Therefore, speed is not included in the formulation of rolling resistance for heavy-duty vehicles.

2.4.2 Air Resistance

Air resistance is the force exerted on a vehicle by the pressure of air. At speeds above 30 mph, this resistant force becomes particularly important, especially for vehicles with large frontal areas. For example, a heavy-duty vehicle travelling at a constant 70 mph on a level grade will require 60% of its tractive effort to overcome the resistance of still air (Western Highway Institute, 1978). Of all the resistance forces, only air resistance is unaffected by the weight of the vehicle.

Air resistance can vary significantly based on local atmospheric conditions due to variances in air density. For example, air density at sea level is nearly one-third greater than at 4,000 feet elevation. Air resistance for still air can be computed by the following equation (Bosch, 1996):

$$F_L = 0.5 * Q * c_w * A * (v + v_o)^2$$

where

F_L is the aerodynamic drag in N,

Q is air density in kg/m^3,

c_w is a drag coefficient,

A is frontal cross-section of the vehicle in m^2,

v is the speed of the vehicle in m/sec.

v_o is the headwind speed in m/sec.

2.4.3 Grade Resistance

Grade resistance is the force of vehicle weight acting at an angle. The magnitude of grade resistance is influenced only by the vehicle weight, and not at all by the vehicle speed. The grade resistance force can be calculated in the form (Bosch, 1996):

$$F_{st} = W * \sin (á)$$

where

F_{st} = grade resistance force, in N.,

W = the gross vehicle weight, in kg, and

á = the angle of incline of the grade.

2.4.5 Chassis Resistance Forces

There are numerous other forces that act in opposition to free motion of heavy-duty vehicles. The power lost due to transmitting engine power to tire-road surface contact area is due primarily to chassis resistance forces, also referred to as driveline resistance. Driveline resistance power losses occur in the transmission, universal joints, axle differentials, seals, and bearings due to mechanical friction and oil stirring. The magnitude of the loss is related to the friction quality of the wearing surfaces as determined by the composition and finish of the surfaces and the efficiency of the lubrication. The viscosity of the lubricants, particularly in the gear box, along with ambient temperature, tire slip, and vehicle speed can also add to the driveline loss of a vehicle. Additionally, up to 10% of power is generally estimated to be lost from the power loss associated with the operation of accessories such as air conditioning and refrigerant (Western Highway Institute, 1978).

2.5 Horsepower Characteristics

2.5.1 Horsepower Requirements

The combination of resistance forces on heavy-duty vehicles requires sufficient tractive force capability to deliver driveability for a range of road conditions. The tractive effort capability is the maximum force a vehicle can deliver against the ground at the driven wheels when the coefficient of traction is not a limiting factor. This capability is most easily measured as the gross horsepower of the vehicle. It is the property of the powered unit alone and does not change when the truck or tractor is coupled with trailers or in various states of loading.

In addition to having enough power to overcome all the negative resistance factors that work to prevent motion, it is desirable that the tractive force capability exceeds the resistance sufficiently to provide an adequate margin of safety and economy. The amount of necessary surplus tractive effort capability depends on the location and physical characteristics of the highways traveled, the importance of the time-distance factor in operating costs, the traffic characteristics of the highways, and any special performance requirements that may be imposed by regulatory agencies.

2.5.2 Horsepower, Torque, and Engine Speed

Total resistance force is transferred to the engine through the crankshaft. The engine speed is measured by the crankshaft in revolutions per minute. The torque is a power measurement that expresses the twisting force on the engine crankshaft. Torque measures the effort used to accomplish an amount of work such as the gross weight that can be hauled.

Horsepower is a value calculated from engine torque and engine speed, and it is the measurement of the speed at which a gross vehicle weight can move over the highway. Horsepower is proportional to engine speed and unlike torque can not be increased or decreased by employing levers or gear ratios. One horsepower is measured as 33,000 foot-pounds per minute measured at a specific testing brake.

In practical terms, torque determines the ability of the vehicle to negotiate a grade, while horsepower determines the speed at which a vehicle can negotiate a grade. On modern highways, there are less requirements for trucks and truck combinations to be able to negotiate grades than for local roads. Therefore, the historical approach of scrutinizing torque has been supplanted by the need for high horsepower engines which can provide for steady state highway speeds, even speeds appreciably greater than those legally allowed. Horsepower values are now more applicable to use when determining the power performance requirements of a vehicle. As described in the following section, gross horsepower can also be converted to net horsepower and finally to wheel horsepower more easily than corresponding torque values.

This makes horsepower not only more applicable, but also more practical than torque in measuring the power performance of heavy-duty vehicles.

2.5.3 Horsepower Terminology

There are several different horsepower terms describing slightly different horsepower measurement criteria. Generally, the term horsepower refers to the gross horsepower of the engine. The brake horsepower is the horsepower which diesel engine industry manufacturers advertise for a given model at a governed engine speed at full throttle. It can be referred to alternately as either the gross horsepower at governed speed, nameplate horsepower, or simply horsepower. The horsepower output of any engine sold is customarily guaranteed to be within 3% to 5% of the advertised value for the engine model under ambient atmospheric conditions (output of some engines can vary depending on temperature and altitude conditions).

Before diesel engines are shipped, the engine is placed on an engine dynamometer to make a quality control check for output horsepower, vibration, leaks, and other potential defects. Originally, the dynamometers used a leather friction belt tightened around a rotating drum, referred to as a prony brake, rather than the hydraulic or electric power absorbing devices used today. The horsepower reading derived from the dynamometer was called brake horsepower (bhp) in reference to the prony brake. Although the prony brake is no longer used, the term brake horsepower persists to this day and is commonly taken to mean simply engine output horsepower whether the engine is on an engine dynamometer in the stripped condition (gross brake horsepower) or is installed in the truck (net brake horsepower).

Most U.S. built heavy-duty trucks are built to customer specifications and can feature a wide variety of engine specifications even for a particular truck model. When an engine is installed into a truck chassis, certain demands are made upon the gross advertised horsepower output of the engine. Horsepower demands are required by many internal truck mechanisms including intake piping, exhaust systems, radiator fans, electric alternator, air compressor, and a freon compressor used for air conditioning and hydraulic pumps for power-steered front wheels. The output of the engine after accounting for all of these internal factors is referred to as net horsepower, flywheel horsepower, or clutch horsepower. In practice, the net horsepower is often estimated by subtracting a certain percentage of the gross horsepower depending on which accessories are included with the truck.

2.5.4 Trends in Horsepower Design

Recent engine designs have been trending towards increased power performance through a combination of high horsepower engines capable of high torque rise. These new designs require maximum power output over a broader and more economical engine range (usually at 1300-2100 rpm). The market for small diesel truck engines (less than 225 horsepower) has also been increasing along with the demand to bring diesel operating economy to the smaller classifications of the heavy-duty vehicles used for intracity service. Concurrently, the demand for light heavy-duty gasoline engines is decreasing as cheaper and more fuel efficient diesel engines are being used in smaller vehicles.

The primary factor in determining current horsepower requirements of linehaul intercity tractors is the federal size and weight limitations. When the weight limits were raised to 80,000 pounds, truck operators required higher engine horsepower to maintain driveability for the increased loads. The trend toward higher horsepower has also been accelerated by the recently increased speed limits. Higher horsepower trucks are required to provide sufficient surplus power to negotiate higher speeds without sacrificing driver comfort.

2.5.5 Other Factors Affecting Engine Power

Environmental conditions also affect the operating horsepower of heavy-duty vehicles. Oxygen is potentially a limiting factor for maximum horsepower output of diesel vehicles. Therefore, in elevated temperatures and high altitudes, the maximum horsepower capability of a truck can be reduced. In addition, the atmospheric air temperature and density can have an effect on the efficiency of combustion within the cylinder. Maximum horsepower is also affected by diesel fuel density. As the fuel density increases, the heat content also rises which allows for more power under full throttle conditions. There can be a significant variation in fuel density throughout the country and at various times of the year as fuel suppliers blend fuel to offset the tendency for fuels to constrict during the cold temperatures of winter.

Normal wear also decreases the horsepower of a given engine. As engines age, gaps develop between the piston rings and cylinder walls allowing gas to escape into the crankcase without doing work. Erosion of the fuel injectors and deposits on the interior of the engine also reduces the efficiency of the engine. Restriction of intake air also increases with age as air filters gather dirt over time.

2.6 Heavy-Duty Vehicle Engine and Transmission Characteristics

The majority of heavy-duty vehicles use diesel engines as the power plant. From the perspective of truck operators, diesel engines have significant advantages over gasoline engines, especially for intercity trucks. The pre-tax cost of diesel fuel is considerably less than gasoline and fuel prices are particularly important for heavy-duty vehicle operations given that intercity heavy-duty vehicles can average over 100,000 miles per year. Diesel engines are also more strongly built than gasoline engines out of necessity in order to contain the higher cylinder pressures required for the compression ignition of diesel engines. This translates into diesel engines having lower maintenance costs, greater reliability, and less down time compared to gasoline engines. These advantages offset the higher manufacturing costs of diesel engines.

With respect to fuel economy the efficiency of the combustion of a heavy-duty diesel engine is based primarily on three factors: the engine speed, the type of transmission, and driver behavior. The engine speed category combined with torque requirements determines the range of horsepower designed for a particular vehicle. The type of transmission determines the potential for matching the engine output to the horsepower demands for the range of onroad activities. Driver behavior determines the actual relationship between the engine speed with the horsepower output for each particular driving activity. Speed-acceleration profiles have been developed which characterize truck driver behavior relative to various roadway geometric conditions (Grant, 1998). Skilled driving combined with a wide speed range engine and a close step transmission results in the most fuel efficiency and likely the least amount of overall pollutants for a particular heavy-duty vehicle. As the driving behavior becomes less skillful, the engine speed range is reduced, and the transmission steps widen, the fuel expended and pollutants emitted will increase for heavy-duty vehicle activity.

2.7 Heavy-Duty Vehicle Data Sources

The majority of heavy-duty vehicle weight and horsepower data can be derived from three sources: national truck surveys, regional commercial vehicle surveys, and weigh-in-motion data collection. Unfortunately, generating metropolitan-level estimates from these data sources is limited due to the non-representative sample fleets and high level of spatial aggregation in sample regions.

2.7.1 National Truck Surveys

National truck surveys are generally utilized by transportation agencies for a number of planning purposes including highway cost allocations, truck size and weight limits, user fees of commercial and private vehicles, energy consumption, and other aspects of improving transportation services for shippers and carriers (Bureau of the Census, 1992). The private sector uses the surveys to conduct market studies, evaluate market strategies, and assess the utility and cost of certain types of equipment. However, due to aggregation of data into large geographic boundaries, non-representative samples of heavy-duty vehicle classes, and questionable data collection equipment, the existing truck database is insufficient for estimating heavy-duty vehicle weight and horsepower characteristics in a metropolitan area. Currently, there are four major national truck travel data sources available which feature heavy-duty vehicle characteristics: the Truck Inventory and Use Survey, the Commodity Flow Survey, the Nationwide Truck Activity and Commodity Survey, and the National Truck Trip Information Survey.

The Bureau of the Census conducts the Truck Inventory and Use Survey (TIUS) every five years as part of the Census of Transportation (Bureau of the Census, 1992). The TIUS provides data on the physical and operational characteristics of the national truck population. The TIUS survey consists of questionnaires mailed to a random sample of private and commercial truck owners based on the R.L. Polk national vehicle registration files (Massie, Campbell, and Blower, 1993). In 1992, over 150,000 trucks were surveyed to measure the universe of over 60 million trucks. The questionnaires solicit information on typical configuration and operation of all trucks over a 1-year period. Owners are asked to estimate the number of miles traveled with respect to the sampled vehicle, as well as information on the number of trailers usually hauled, type of cargo usually carried, and the typical weight of a load. Survey samples for the TIUS are created from state and national heavy-duty vehicle registration files.

As a result, the TIUS produces aggregate (state and national level) truck travel estimates and cannot be used to reflect specific metropolitan areas or specific truck configurations.

The Bureau of the Census also conducts the Commodity Flow Survey (CFS) to provide data on goods movement across the range of transportation modes (CTCU, 1992). The CFS is a sample-based survey that disaggregates the movement of goods for over thirty commodity types and nine modes of transportation including courier truck, private truck, for-hire truck, air, and rail. The 1997 CFS contains separate reports developed for the data on the national level, for each of the 50 states, and for 89 National Transportation Analysis Regions (NTARs). The NTARs represent one or more Bureau of Economic Analysis economic areas.

The NTARs are the smallest geographic unit for which CFS data are available. Unfortunately, most of the NTARs include several metropolitan areas, and this limits the usefulness of CFS data to a particular metropolitan area. The NTAR that includes the Atlanta metropolitan area also includes the metropolitan areas of Chattanooga, Tennessee; Columbus, Georgia; Macon, Georgia; and Greenville, South Carolina. Therefore, several supplemental data sources would have to be utilized in order to make conclusions about commodity flows in the Atlanta metropolitan area based on the NTAR-level data.

The Nationwide Truck Activity and Commodity Survey (NTACS) is a detailed annual and daily truck activity database for a sample of trucks covered in the 1987 TIUS (Oak Ridge National Laboratory, 1993). The 1990 NTACS was based on truck operators' response to daily and annual truck activity survey items. The purpose of this survey was to capture temporal and geographic variations in truck travel and other trucking characteristics beyond the scope of the TIUS. The data were collected using a mailout-mailback survey on randomly selected days over a 12-month period ending in October of 1990. The 1990 NTACS sampled 44,002 trucks stratified by geographic division, types of haul, and truck classification. Respondents were asked to report trip activities for 2 selected days in a 4-week period. However, the

NTACS suffered from high item non-response rates and data inconsistency problems. Therefore, the ability to utilize NTACS data for specific metropolitan area truck activity estimates is restricted.

The National Truck Trip Information Survey (NTTIS) was conducted from November 1985 to February 1987 by the Center for National Truck Statistics of the University of Michigan Transportation Research Institute (UMTRI). The NTTIS is a national survey of medium and large trucks. A total of 8,144 commercial vehicles with a weight rating of over 10,000 pounds were selected from the registration list. Similar to the TIUS, the NTTIS used the R.L. Polk vehicle registration files as its sample base, and most of the survey information was collected through telephone interviews with truck owners. However, the NTTIS was based on actual truck trips as opposed to the "typical" trips used in the TIUS. As with the TIUS sample, the NTTIS framework was stratified by state making it difficult to make metropolitan-level inferences from the data collected in the survey.

2.7.2 Regional Commercial Vehicle Surveys

Few urban areas in the country have had extensive experience in conducting truck surveys and forecasting truck travel demand. Most metropolitan planning organizations (MPOs) or regional transportation authorities continue to generate their truck trips based on federally-sponsored roadside origin-destination surveys from the 1960s and 1970s. Since 1980, only a handful of metropolitan areas have undertaken significant efforts to collect truck travel data or develop new techniques in forecasting truck traffic. A recent report (Lau, 1995) summarizes the efforts of truck and commercial vehicle surveys for the following metropolitan areas: Chicago (1986), Ontario (1983 and 1988), Vancouver (1988), Phoenix (1991), New York-New Jersey (1991-1994), El Paso (1994), Houston-Galveston (1994), and a number of metropolitan surveys in California.

Many of these commercial vehicle surveys are supplemented by regionally-based external travel surveys which include a combination of vehicle classification counts and roadside surveys. Along with the Atlanta Commercial Vehicle Survey conducted in 1996, the following section compares the methods, data collected, and survey findings of these recent commercial vehicle surveys. These surveys represent the largest of all of the major data collection efforts underway to understand metropolitan-level truck activity, and they serve as a basis for analyzing the strengths and weakness of the current truck activity data inventory.

2.7.2.1 Survey Methods

The two most common types of truck surveys are trip diaries and roadside surveys. Trip diaries are the most common method for conducting regional truck travel surveys that often serve as the basis of metropolitan-level heavy-duty vehicle activity estimation. These trip diaries generally use a combination of telephone-mailout-mailback methods to collect data. Generally, the survey sample for trip diaries is developed from the state Department of Motor Vehicle (DMV) registration files. Other samples include lists of truck registration files available from commercial sources (R.L. Polk, Texas Vehicle Information, and Computer Services, Inc., etc).

Roadside interviews are the second most common survey method. They tend to produce a high response rate (nearly 100 percent). They are generally used for cordon surveys or surveying trucks with at least one origin or destination outside of a particular urban area. A variation of the roadside survey includes video or automated truck data collection programs. The California truck surveys included a combination of videotaping freeway traffic flows at 78 urban freeway sites and trip diary surveys in the Los Angeles, Sacramento, and San Francisco metropolitan areas.

2.7.2.2 Survey Data Items

The most common types of data collected in the truck surveys included: gross vehicle weight ratings, number of axles, truck type, origin-destination information, commodity type, land use, driver information, and route information. Figure 4-2 shows the particular data items included in each of the survey efforts for these broad data categories.

Survey Location	Survey Year	Survey Method	Sample Source	Weight	Axle	Truck Type	O-D	Odometer	Commodity	Land Use	Driver Info	Route Info
Chicago	1986	Mail	DMV									
Ontario	1988	Roadside	Roadside									
Phoenix	1991	Phone /Mail	DMV									
N.Y. & N.J.	1991	Roadside	Toll Plaza									
Alameda County, CA	1991	Phone /Mail/ Road	DMV, Port, Road									
N.Y. & N.J.	1992-1994	Roadside	Roadside									
El Paso, TX	1994	Phone	Private /DMV									
Houston	1994	Phone /Mail	DMV									
Atlanta	1997	Phone /Mail	DMV									

Figure 4-2: Recent Truck Travel Surveys and Types of Data Collected (Lau et al, 1995 and Atlanta Regional Commission, 1997)

2.7.2.3 Survey Findings

Many of the metropolitan-level surveys are based on samples that are not representative of the regional heavy-duty truck activity. In addition, the failure to include sufficient spatial factors and detailed data on vehicle characteristics in many of the surveys limit the use of these data for emissions modeling.

2.7.2.3.1 Inadequacies of HDV Fleet Representation. Most of the regional survey samples were not disaggregated by vehicle classification. This often resulted in insufficient sample sizes for heavy-duty vehicle modeling. For example, the Atlanta commercial vehicle survey developed its sample based on the commercial vehicle registration database without prior consideration of heavy-duty vehicle fleet representation. Because light-duty vehicles dominate the commercial vehicle fleet, the proportion of heavy-duty trucks included in the survey is too small to create a statistically significant heavy-duty truck activity model.

Single-unit and combination trucks comprise 7% of the vehicles included in the Atlanta External Survey. However, because VINs were not collected as part of this survey, detailed information on heavy-duty vehicle characteristics can not be generated.

2.7.2.3.2 Inadequacies of Trip Type Representation. Many surveys indicate that trucks registered outside of the local study area generate the majority of truck trips in the metropolitan area. The Chicago survey found that 73.8% of the vehicles included in the survey based on International Registration Plan (IRP) plates were registered outside the six-county study area. The Los Angeles County truck survey based on a total of 65,346 freight bills found that 2/3 of all truck trips were a result of activity external to the metropolitan area (SCAG and Caltrans, 1979). 35% of the freight bills were from through truck trips for the region; 31% of the freight bills had one of the trip ends outside the region; and only 33% of the freight bills showed both origins and destinations inside the study area.

These results imply that for Atlanta, which is geographically located in between many major metropolitan areas in the south, a high percentage of heavy-duty vehicle activity will be generated by external activity. However, the commercial vehicle survey for Atlanta collects data only for trips with both origins and destinations inside the 13-county Atlanta metropolitan area. Truck surveys that are based on local vehicle registration files (e.g. Atlanta) are likely to represent a limited proportion of the overall truck activity, particularly for Interstate truck traffic and traffic for the larger heavy-duty vehicles.

2.7.2.3.3 Temporal Variability. The 1985 New York truck survey showed that there is a difference in the temporal distribution of various goods. Commodity types were divided into several categories including food, paper, furniture, apparel, and chemical movements by hour from roadside truck surveys (Wegmann, 1994). The survey showed that there were hourly fluctuations in the truck volumes of each of the commodities based on day of week and time of day. This indicates that temporal fluctuations will also exist for the weight distribution data set collected in a metropolitan area.

2.7.2.3.4 Inadequacies of Spatial Representation. Most of the survey samples were not disaggregated by smaller geographic regions which led to sample sizes in certain regions which are too small to create statistically significant heavy-duty vehicle models. The Atlanta survey randomly sampled firms that owned commercial vehicle without accounting for spatial representation throughout the 13-county area. In Atlanta the result was that four of the thirteen counties had only one firm represented in the overall sample population. This reduces the ability of the survey to recognize spatial variability in truck activity.

2.7.2.3.5 Inadequacies of Heavy-Duty Vehicle Weight Data. The Houston and Ontario surveys requested truck owners to estimate the average onroad GVW of each commercial vehicle in their fleet. The only survey that reported onroad gross vehicle weight for each truck trip was the 1991 Phoenix Commercial Vehicle Survey. However, the purpose of the Phoenix survey was to develop new models only for commercial vehicle trips with both origins and destinations inside the metropolitan study area. As mentioned previously, internal-internal trips are generally a small portion of the overall metropolitan heavy-duty vehicle activity, and therefore weight models developed in Phoenix can not be generalized to the entire Phoenix metropolitan truck traffic fleet or to other metropolitan areas. The failure to include onroad gross vehicle weight in commercial vehicle surveys results in the inability to develop the relationships between weight and the spatial and temporal variability of truck activity.

2.7.3 Weigh-In-Motion Sites and Equipment

2.7.3.1 Weigh-In-Motion Sites

The development of a vehicle weight program for the purpose of generating emissions estimates is a new practice in transportation. Currently state transportation agencies and state highway patrols are the two primary operators of weigh-in-motion (WIM) programs. The majority of the sites are permanent WIM locations selected to monitor the weights experienced by bridges and specific roads (Cambridge Systematics, 1994 and Chira-Chavala, 1986). These permanent sites are generally located far from the metropolitan areas that are important for emissions estimation. In Georgia, none of the permanent WIM sites used for statewide truck weight data collection are located inside the 13-county study area of this research. Data collected from portable sites are inaccurate due to ineffective calibration techniques and equipment sensitivity to changes in temperature.

A North Carolina study characterized weight distributions throughout the state using the state's system of permanent WIM sites (Dahlin, 1992). The study developed a set of load factors that can be applied to statewide traffic classification counts to estimate network traffic loading history. Three years of WIM data at 23 locations in North Carolina were used to determine the variability in truck weights for particular truck weight classes. Separate weight distributions for three classes of trucks were developed (single-unit trucks, single-trailers, and multi-trailers) at each particular site. There was no significant statistical difference between truck weights on a seasonal basis at a particular site, but there was not enough data to conclude what differences might occur on the weekends. This data supports the research approach of this dissertation of assuming that weight distributions vary by time of day and day of week, but not by seasonal factors. However, the inclusion of a significant portion of rural heavy-duty vehicle weight data limits the application of these results in metropolitan areas.

2.7.3.2 Weigh Station Data

State highway patrols use WIM programs to enforce federal and state regulation on the weights of vehicles that travel on the Interstate System. Weigh stations are located along Interstate highways, usually near the border between states. All trucks are required by law to be weighed at the weigh station during its hours of operation. The hours of operation of weigh stations in Georgia are usually between 9AM and 4PM. However, hours are occasionally altered and can range from random to continuously open. Trucks that are found to be over the legal limit by the scales at the weigh station are fined and allowed to continue to travel along their routes. Vehicles that are severely overweight are required to return to their origin and unload or reload.

Of the 12 weight enforcement stations in Georgia, only the Douglas County weigh station is located inside the study area. Unfortunately, equipment capabilities at the weigh station do not allow for electronic storage of data collected at this location. Data collected manually at this weigh station have two major limitations. First, the data are limited to the operating hours of the weigh station. Generally weigh stations are open only during the day, depending on the nature of the specific WIM equipment at a particular station. Second, data are limited by the evasion of weigh stations by a fraction of trucks. Truck drivers that knowingly are travelling above the legal limits of the state often use alternative routes to avoid being fined or re-routed by weigh station officers. As mentioned in Chapter 1, The Florida DOT undertook a study to asses the magnitude of the problem of overweight truck weight enforcement station avoidance. The report shows that during the hours between midnight and

6AM, there are a significant number of trucks that systematically avoid weigh stations. Additional research showed that a 58 percent increase in truck volume on a bypass route 30 miles from the study corridor and a 3 percent increase on a bypass route 80 miles from the corridor occurred as temporary weight enforcement stations were installed on a primary route (Cunagin, 1997).

2.7.3.3 Weigh-In-Motion Accuracy

The issue of WIM accuracy is complicated by the phenomenon that in-motion axle loads can differ substantially from static axle loads due to pavement roughness-induced vehicle dynamics. A comprehensive state-of-the-art NCHRP report discusses this dynamic load variation (Gillespie et al, 1993). Computer simulation methods are often used to estimate this component of the variability (Pappagianakis, 1995). The variability between static and in-motion axle loads is due to two separate components:

1) the difference between the dynamic load applied to a WIM sensor the instant an axle is directly over it and the static load of this axle, and
2) the inherent error of the WIM system in measuring the dynamic load applied.

The American Society for Testing and Materials (ASTM) has developed a standard specification for highway WIM systems. The standard specifies that each type of WIM system shall be capable of performing weight measurements within 15% for heavy-duty vehicles gross weight and 30% for a single axle weight for 95% of all vehicles weighed. However, an extensive system of in-motion and static vehicle weight scales are required to calibrate the equipment to meet these specifications making it impractical for most weight data collection locations.

For this research, portable WIM equipment is used to collect heavy-duty vehicle weight data throughout the Atlanta metropolitan area. The weight models developed in this research are generated through the application of a post-processing method designed to minimize the temperature and road surface sensitivities of the portable WIM equipment. The use of electronic equipment will allow for temporal characterization of several heavy-duty classifications. The portability of the equipment allows for the selection of several, spatially relevant sites to be included in the vehicle weight data collection sample.

To characterize the onroad engine distribution of the heavy-duty vehicle fleet, roadside truck surveys are conducted at several locations. The surveys are designed to match heavy-duty vehicle classification data with horsepower data, in addition to collecting information on vehicle weight, vehicle body type, truck company type, and origin-destination information when possible. Spatial and temporal specificity of the horsepower distributions will also be included in the surveys to allow for incorporation into emissions models.

CHAPTER III

3. HEAVY-DUTY VEHICLE EMISSIONS

As a result of heavy load and power requirements, the emission levels of heavy-duty vehicles are higher than those of passenger cars on a gram-per-mile basis. Therefore, despite the smaller percentage of heavy-duty diesel vehicles in the overall vehicle fleet, diesel emissions are an important fraction of the overall emissions inventory. However, differing combustion processes and the increased size of diesel engines cause the emissions properties of diesel engines to differ from that of gasoline engines. This has led to differences in air pollution standards for the different vehicle types, and the development of separate modeling regimes for diesel and gasoline-powered vehicles.

This chapter examines the diesel fuel combustion process and its relationship to diesel engine emissions formation followed by a summary of the emissions standards for diesel engines. The chapter concludes with a look at the conventional emissions modeling regime and a new modal emissions model currently under development.

3.1 Diesel Fuel Combustion

The formation of emissions in diesel-powered vehicles is primarily a product of the combustion process. The essential features of the diesel engine combustion process are the injection of liquid fuel into the cylinders as the pistons approach dead center and a compression ratio of 12 to 13 parts air to 1 part fuel to initiate the combustion process. The unique properties of the combustion system of a diesel engine are determined by its combustion chamber and the fuel injection system.

As the combustion process begins, liquid fuel jets are injected at high pressure into the combustion chamber. Within the chamber, the jets disintegrate into a core of fuel surrounded by an envelope of air and fuel droplets. By this time the combustion process has caused the air temperature within the chamber to increase to the level required to ignite the fuel. The combustion process is usually divided into four stages:

1. an ignition delay period, during which time the fuel is atomized, vaporized, partially mixed with air, raised in temperature, and ignited;

2. a period of rapid pressure rise, which is largely the result of the combustion of the pre-mixed air and fuel vapor formed during the ignition delay period;

3. a period of controlled pressure rise, which is associated with fuel vaporization and the diffusion controlled burning of the fuel; and

4. a late burning period, which occurs during the expansion stroke and is critical in determining the final pollutant emission levels.

The length of period of the initial phase of diesel engine combustion is decided by the quality of the fuel, the engine temperature, the pressure of compression, the initial rate of fuel injection, and the form of the combustion chamber. Thereby, all of these factors influence the entire combustion process including fuel efficiency, engine noise levels, and pollutant formation.

3.1.1 Fuel Injection

The fuel injection system is the key mechanical component of the diesel engine. Extremely high injection pressures (130 to 1,300 atmospheres) are needed to assure that injection, atomization, and vaporization occur within the short time available. The injection system must:

- meter the quantity of fuel needed for different engine speeds and loads,
- distribute the fuel equally among the different cylinders,
- inject the fuel at the proper time in each cylinder cycle,
- inject the fuel at the proper rate,
- produce the spray pattern and atomization required by the combustion chamber design, and
- complete the injection cleanly without dribbling or after-injections.

Power in diesel engines is controlled by varying the fuel supply into the engine. Electronic controls in the engine predict when additional engine speed is required and the level of fuel is adjusted accordingly. Many diesel engines are turbocharged which substantially increases the fuel supply for extreme high engine load conditions. Turbocharging increases the temperature and pressure of the combustion process. Therefore, aftercooling technology, which sprays water into the combustion process, is often employed in turbocharged engines to keep the engines from overheating.

3.1.2 Comparison with Gasoline Engines

The primary difference between diesel and gasoline combustion is that diesel power is altered through varying the amount of fuel supplied to the engine, while gasoline engines vary the amount of air supplied to the engine. As a result, for most operating conditions, diesel engines operate with excess air and gasoline engines operate with excess fuel. Throttling the fuel also generally results in a very efficient use of the fuel in diesel engines, thereby adding to the fuel efficiency of diesel engines. In addition, the density of diesel fuel has approximately a 13% greater energy content than gasoline. This energy differential is another of the factors in the diesel fuel economy advantage. The fuel saving effect is compounded by the fact that diesel engines do not use overall fuel-rich mixtures during the initial operation.

The injection phase of the diesel combustion process also differs from the combustion of gasoline-powered engines. The first phase of the diesel combustion process is the injection of the diesel fuel into the combustion chamber. At this point, the ignition has been initiated, but there is no measurable difference between the pressure and the air compression in the chamber. Therefore, diesel combustion occurs by compressing the volume while keeping the pressure constant. This process contrasts from gasoline engine combustion in which the entire combustion process occurs at near constant volume while increasing the pressure. The fuel injection process contrasts with the flame propagation technique of combustion used in gasoline engines.

3.2 Diesel Engine Emissions Formation Process

The combustion process produces four emission pollutants of primary concern: carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), and particulate matter (PM).

3.2.1 Carbon Monoxide

Under ideal combustion conditions, the carbon in fuel mixes with oxygen from the air to create carbon dioxide as an exhaust product. However, when there is insufficient oxygen in the combustion chamber, some of the carbon does not completely oxidize and carbon monoxide is formed. In diesel exhaust carbon monoxide levels are relatively low due to the excess of oxygen available in the combustion process. Even at maximum power output, there is as much as 38% excess air in the combustion chamber. This leaves only a brief interval after the start of injection for fuel to mix with air, thus converting only about 75% of the air to carbon dioxide (Newton et al., 1996).

3.2.2 Hydrocarbons

As with the carbon in carbon monoxide exhaust, hydrocarbons are present in the fuel and are usually transmitted to the exhaust through some form of incomplete combustion. For heavy-duty diesel engines, there are three main conditions which can result in diesel engine hydrocarbon emissions:

1) maximum power output,

2) light loads or low temperatures, and

3) engine start and warm-up activities.

Maximum power output of heavy-duty vehicles generally occurs near or above the gross vehicle weight rated limit for the particular vehicle classification. Also, maximum power may be necessary to maintain a certain speed on a grade or while accelerating from low to high speeds. To achieve maximum power output, fuel delivery to the combustion chamber is increased. As the fuel delivery is increased, a critical limit is reached above which the oxygen in the air is insufficient to efficiently combust all of the fuel. This causes hydrocarbon exhaust output to rise steeply. Although some fuel injection systems are set so that fueling does not rise above the critical limit, many diesel engines intentionally forego this feature to allow for these high power output conditions.

Extremely low power operations can also result in unburned hydrocarbon emissions. Under these conditions when fuel is mixed in regions where there is too much air and the temperature is too low to promote complete oxidation, hydrocarbon and partially oxygenated hydrocarbon emissions sometimes result. At low temperatures or light loads, the low levels of fuel required by the engine often results in a very lean fuel-air mixture. During the pre-combustion process of the ignition delay period, the lean fuel inhibits the complete combustion inside the pre-combustion chamber, and some of the mixture fails to burn resulting in unburned hydrocarbon emissions.

The low volatility of diesel fuel combined with the short period of time available for it to evaporate before combustion begins result in hydrocarbons being generated during the start-up and warm-up for cold engines. During warm-up conditions, the low engine temperatures result in a higher than normal proportion of the fuel injected into the combustion chamber being completely combusted. Therefore, some of the fuel fails to evaporate and is deposited on the combustion chamber walls. This further reduces the fuel evaporation rate, so that the fuel fails to be ignited before the contents of the chamber have been cooled during expansion. Similarly, the cooling effect of the expansion stroke when the engine is operating at or near full load can lower the efficiency of combustion in areas of the mixture with high fuel-air ratio content.

A late fuel delivery system, particularly fuel coming from the injector sac volume, can also contribute to unburned hydrocarbons in the exhaust. The last portion of the fuel being injected is poorly atomized because the injection pressure is lower and the combustion chamber is higher; thus locally there is not enough air to completely oxidize the hydrocarbons. Wall impingement by the fuel, which is a special problem in small, high-speed direct injection engines, also contributes to unburned hydrocarbons and particulate emissions.

3.2.3 Oxides of Nitrogen (NO_x)

High-temperature oxidation of molecular nitrogen leads to the formation of oxides of nitrogen (NO_x). Atmospheric air is generally about 80% N_2 and 20% O_2, but these elements are stable because of the moderate temperatures and pressures. However, during high temperature and pressure conditions of combustion, excess oxygen in the combustion chamber reacts with N_2 to create NO which is quickly transformed into NO_2.

NO_x is a very important diesel engine pollutant, because mobile sources are the primary sources for NO_x emissions. Diesel engine pollutant levels can be up to ten times as high as gasoline engine emission levels. This is a result of the necessity of extremely high temperatures and pressures for diesel fuel combustion and the tendency for the combustion chamber to contain excess air. In addition, because of the direct relationship between NO_x emissions levels and engine load conditions, NO_x emissions are an important pollutant to consider in understanding the effects of high power vehicle operating conditions.

3.2.4 Particulate Matter

The highly stratified mixture of fuel and air in the diesel engine results in fuel-rich zones within the combustion chamber. The combination of these fuel-rich zones and high temperatures leads to the formation of carbonaceous particulate, often referred to as soot or more recently as particulate matter.

The sulfur in diesel fuel generates particulate matter. Particulate formation begins when the fuel is injected into the combustion chamber and continues during and after the dilution of the exhaust in the atmosphere. The first stage of the process occurs within the first milliseconds. The last steps may take hours or even days.

Although most particulate emissions are formed through incomplete combustion of diesel fuel hydrocarbons, previous studies indicate that up to 25% may be contributed by the engine oil and that fuel components other than hydrocarbons may also contribute. The introduction of small amounts of engine lubricants into the combustion chamber can also contribute to diesel particulate emissions.

3.2.5 Other Pollutants and Irritants

Diesel engines emit high levels of aldehydes, nitrogen dioxide, and sulfur dioxide (due to the sulfur in diesel fuel) relative to gasoline engines. Aldehydes, which are unregulated, have high photochemical reactivities and are largely unaccounted for by current hydrocarbon emission assessments. Sulfur-contained compounds are emitted in the exhaust of diesel engines, because sulfur exists as an impurity of the fuel. Most of this sulfur is emitted as sulfur dioxide. The sulfur concentration of diesel fuel is expected to increase because of the deteriorating quality of diesel fuel. Diesels are also typically noisier than gasoline vehicles particularly during idling and under light load conditions.

HC exhaust emissions combined with the lubricating oil are the principle cause of the unpleasant smell of diesel engines. Black smoke in diesel engines is a consequence of incompletely burned fuel in the exhaust. The presence of black smoke increases with fuel density and the carbon content of the fuel. Black smoke also tends to increase as a result of the various NO_x reduction measures as do other particle emissions. The diesel combustion process produces vaporized water droplets. The temperature of these droplets fails to rise sufficiently for ignition creating fuel droplets. In cold temperature conditions, fuel droplets mix together with water vapor produced by the burning of hydrogen content in the remainder of the fuel. This process forms a mixture of fuel and water vapors from the exhaust pipe, generally referred to as white smoke.

3.2.6 Emissions Comparison with Light-Duty Gasoline Engines

As mentioned earlier, the high temperatures and pressures of diesel combustion combined with the heavy loads of heavy-duty vehicles result in levels of NO_x emissions that are significantly higher than that found in light-duty gasoline vehicles. Levels of hydrocarbons tend to be equivalent for diesel and gasoline engines that are the same size. The larger emission rates from HDVs tend to be primarily a result of the larger sizes of their engines. Carbon monoxide levels of HDVs are relatively very small compared to gasoline engines due to the low levels of excess oxygen in light-duty gasoline engines which are throttled using the supply of air.

Particulate emissions are particular to diesel fuel combustion, and exist in minimal levels in gasoline engines.

3.3 Emission Control Techniques

Formation of particulates is fundamental to the combustion process in diesel engines, but emissions of these particles in diesel exhaust is not, because the particulate finally emitted in diesel exhaust is the result of both formation and subsequent oxidation processes. Experimental evidence from a variety of combustion systems and fuels indicates that chemical kinetics is the dominant factor governing the formation and oxidation of particulates. A combination of high mixing rate and long ignition delay to approach premixed, homogeneous conditions has been shown to reduce particulate emissions.

However, ignition delay times characteristic of current diesel fuels are too short to accomplish this using known mixing technology, and if longer mixing and ignition times were permitted, the increased peak cylinder pressures that resulted would cause serious structural problems. Thus, the current approach is to optimize particulate emissions through programmed fuel injection and system components that control the rate and intensity of combustion.

Measures taken to reduce NO_x tend to increase the quantity of particulates and HC in the exhaust. This is primarily because, while NO_x is reduced by lowering the combustion temperature, both PM and HC are usually burned off by increasing the temperature. However,

NO_x output becomes significant only as maximum torque and power are approached. At lighter loads, the gases tend to become cooled because of both the excess air content and the large expansion ratio of the diesel engine.

Because the proportion of excess air falls as the load increases, oxidizing catalysts can be used in the smaller of the heavy-duty diesel vehicles without risk of overheating, even at maximum power output. However, for most heavy-duty vehicles, present catalytic converters can not be used because of excess oxygen and clogging by particulates. Considerable control has been made in reducing diesel emissions by means of electronic control systems that adjust fuel quantity, injection timing, and exhaust gas recirculation to many operating variables influencing emissions.

Exhaust gas recirculation (EGR) displaces oxygen that would otherwise be available for combustion and thus reduces the maximum temperature. However, it also heats the incoming charge, reduces power output, causes both corrosion and wear, and leads to smoke emission at high loads. For these reasons it has to be confined to operation at moderate loads. Generally, heavy commercial vehicles are driven most of the time in the economical cruising range, maximum power and torque being needed only for high engine load conditions. Therefore, electronic control of EGR is desirable to differentiate between moderate and heavy loads.

3.4 Relationship of GVW and HP to Diesel Emissions

Gross vehicle weight and horsepower are two important factors in determining the load on an engine. For a particular truck, the gross vehicle weight can vary by a factor of between 2 and 3. For example, a small 2-axle truck can range between 6,000 pounds when empty up to over 20,000 pounds when fully loaded depending on the gross vehicle weight rating of the vehicle. The gross vehicle weight of a typical large truck generally ranges from just over 30,000 pounds when empty up to and beyond the federal legal limit of 80,000 pounds when fully loaded.

Increases in engine load are matched by an increase in the supply of fuel to the engine as the driver shifts to lower gears. This increases the fuel-air ratio of the engine which in turn affects the emission rates of the combustion process. NO_x emissions will increase as the combustion temperature and pressures increase to accommodate the combustion of the fuel-rich mixture in the chamber and an increased engine load. CO emissions will increase as the amount of excess oxygen in the combustion chamber decreases and more of the carbon from the fuel fails to convert into CO_2. Under situations of extreme engine loading the emissions of particulates and hydrocarbons can increase as the highly stratified diesel fuel-air mixture has an increase in pockets of fuel which fail to burn completely. However, generally this factor is offset by the more complete combustion in the entire chamber that tends to occur as the combustion temperature increases and there are less unburned particles in the exhaust.

Under identical driver behavior, higher horsepower engines will operate at less than full throttle for a larger percentage of their operating conditions than lower horsepower engines. At less than full throttle, there is less stress on the vehicle, and the engines are more likely to run lean as the fuel requirements to accommodate the power lessen. Therefore, the combustion temperatures and pressures are decreased which serves to decreases the emissions of NO_x. In addition, the excess oxygen keeps the emissions of CO minimal. However, the decreased loading on the engine will increase PM and HC emissions as the fuel fails to burn completely.

It should be noted that there is potentially a relationship between the horsepower of an engine and driver behavior. Drivers of high horsepower engines likely drive at faster speeds which has the effect of increasing the engine load and counteracting the generally advantageous emissions characteristics of high horsepower engines relative to low horsepower engines. NO_x output depends on both the peak temperature of combustion and also on the rate of rise and fall to and from the peak combustion temperature (Newton et al, 1996). Therefore, factors such as the engine torque and driver behavior along with horsepower and gross vehicle weight, will also play important roles in the emission formation of this pollutant.

Generally, the lowest emissions levels will occur for vehicles with light loads and high horsepower engines. The actual emissions for a particular vehicle may be more complicated, because for some engines light load and low power operating conditions can increase HC and PM emissions. This can occur through the failure of lower combustion temperatures to completely burn these pollutants from the fuel. There are also often tradeoffs between reductions in levels of NO_x and reductions in levels of HC and PM. However, over the range of all heavy-duty engines and the entire range of driving conditions, emissions tend to be lower for high horsepower heavy-duty vehicles with light to moderate gross vehicle weights.

3.5 Air Pollution and Engine Emission Standards

3.5.1 Air Pollution Standards

National Ambient Air Quality Standards (NAAQS) were established by the U.S. Environmental Protection Agency (EPA) to protect public health (40 CFR 50). The six criteria pollutants currently included in the NAAQS are carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter with an aerodynamic size less than or equal to 10 microns (PM_{10}), sulfur dioxide (SO_2), and lead (Pb) (40 CFR 50). The greenhouse gas, carbon dioxide (CO_2) is also of concern, because it traps the heat energy of the earth contributing to global warming. The operation of diesel vehicles contribute to all of the criteria pollutants except for lead which was also phased out from gasoline vehicles in the late 1980's.

Carbon monoxide is a colorless odorless gas that upon entering the bloodstream reduces the delivery of oxygen to the body's organs and tissues. Inhalation of CO is especially harmful to infants and the elderly. Automobiles are the primary source of carbon monoxide in urban areas.

Nitrogen dioxide serves as an irritant to the lungs. It can reduce the body's resistance to respiratory infections. NO_2 is also a strong oxidizing agent that reacts in the atmosphere to form corrosive nitric acid. Nitrogen dioxide has several significant atmospheric effects including decreasing visibility and contributing to property and plant damage.

Oxides of Nitrogen (NO_x) are a precursor to the formation of ozone (O_3). Ozone is formed from the chemical reaction of NO_x and volatile organic compounds (VOCs) stimulated by sunlight. The chemical reaction can occur at a completely different location and time than where the precursor gases are emitted making ozone the most complex and difficult pollutant to control. The effects of ground level ozone include damage to lung tissue, reductions in lung function, and the sensitization of the lungs to other irritants. Even in healthy individuals, extended exposure to ozone causes choking, coughing, aggravates respiratory disease, and increases respiratory infections. Children are particularly sensitive to ozone, but even at low doses, continual exposure over a period of six hours can reduce lung function and induce respiratory inflammation in healthy adults. Ozone can also cause damage to crops and forests along with decreasing the growth of plants.

Sulfur dioxide is an eye and respiratory irritant. It is also of concern as an exhaust pollutant because it undergoes further oxidation in the atmosphere to form sulfuric acid, which in turn is the most significant cause of acid rain. Although most sulfur dioxide is emitted from stationary sources like power plants, the sulfur from diesel fuel is often included in the exhaust pollutants of diesel vehicles.

Particulate matter is a major health concern because it can lodge deep in the lungs, causing asthma, bronchitis, decreased lung capacity, respiratory trauma, and premature death. The smallest of the particulate matter, less than 2.5 microns, has recently been identified as being particularly harmful, because the human body has great difficulty in removing these particles after they have been inhaled. The EPA has recently included $PM_{2.5}$ in the air quality standards along with more stringent standards for PM_{10}.

3.5.2 Engine Emission Regulations

Engines of automobiles, trucks, tractors, locomotives, marine vehicles, and aircraft have air pollutant emission standards developed by the EPA. The trend with vehicle emission standards is to lower the maximum emissions over time to allow for the development of vehicle technology to meet increasingly stringent standards. Heavy-duty vehicles are actually regulated indirectly through emission limits placed on the heavy-duty diesel engines that power the vehicles. In terms of the percentage reduction from non-regulated emission levels, the emissions from heavy-duty diesel engines have been less regulated than other mobile sources. This makes diesel engines a likely target of future tightening of emission standards.

The heavy-duty diesel exhaust pollutants regulated through EPA standards are CO, HC, NO_x, non-methane hydrocarbons (NMHC), particulate matter, and smoke. Each of the heavy-duty pollutants is regulated over what is considered the "useful life" of the engine which is the minimum of either 8-10 years or 110,000-290,000 miles depending on the classification of the vehicle.

Because diesel engines operate with excess oxygen, the combustion process is uniform relative to gasoline engines. Therefore, the instantaneous emissions levels are highly correlated with the instantaneous work output of the engine. This allows diesel engine emission levels to be expressed as units of pollution per unit of work done by the engine, grams per brake-horsepower-hour (g/bhp-hr), as measured over a specified test cycle on an engine dynamometer.

Gasoline engines have a much more erratic combustion process as a result of the excess fuel generally present during combustion and the variation in the percent of fuel utilized for a particular stroke. This produces a wide range of instantaneous emissions levels for a specific work output level of the engine. Therefore, instantaneous emissions levels are averaged over distance and are estimated in the units of grams emitted per distance traveled (g/mi.).

Figure 3-1 shows the EPA standards for CO, HC, NO_x, PM, and smoke since 1990 for heavy-duty diesel engines. In the test laboratory, the emissions are mapped as contours that are a function of engine load and speed. These data may be used to predict the performance of vehicles over arbitrary driving conditions. Class-specific conversion factors have been developed to convert from g/bhp-hr to g/mi. to predict performance of vehicles over arbitrary driving conditions.

	1990	1991-1993	1994-1997	1998+
CO (g/bhp-hr)	15.5	15.5	15.5	15.5

HC (g/bhp-hr)	1.3	1.3	1.3	1.3
NO_x (g/bhp-hr)	6.0 (NCP)	5.0 (ABT, NCP)	5.0 (ABT, NCP)	4.0 (ABT, NCP)
PM (g/bhp-hr)	0.60 (NCP)	0.25 (ABT, NCP)	0.10 (ABT, NCP)	0.10 (ABT, NCP)
Smoke % (acc/lug/peak)	20/15/50	20/15/50	20/15/50	20/15/50
Warranty Period	5 years/100,000 miles (but not less than the basic mechanical warranty for the engine family)			

Figure 3-1: EPA HDDE Standards for CO, HC, NO_x, PM, and Smoke

In-use emissions of all engines, including heavy-duty diesels, are often significantly greater than certification emissions. This is the result of the effects of production tolerances in manufacturing, user tampering with emission controls, poor engine maintenance, use of poor quality fuel, and other causes. The effects of tampering and malmaintenance on in-use emissions are discussed in a report to the Air Resources Board (Sierra Research, 1987).

In addition, all of the critical emissions-related components on a heavy-duty engine are rebuilt or replaced during engine overhaul. Engine overhauls are generally undertaken on heavy-duty diesel engines after several years of use to reestablish the fuel economy and engine reliability of the vehicle without regard to the emissions performance of the vehicle. This may be a significant omission from heavy-duty vehicle emissions inventories. However, because the engines of intercity heavy-duty vehicles are generally newer than the overall heavy-duty vehicle fleet, this omission is likely less significant for Interstate travel than for non-Interstate travel.

The EPA also regulates evaporative hydrocarbon emissions of heavy-duty diesel engines. Evaporative hydrocarbons are volatile organic compounds which escape into the air through fuel evaporation due to diurnal temperature changes, running losses, hot soaks, and refueling. The regulations include limits on diurnal plus hot soak, three-diurnal test sequence, supplemental two-diurnal sequence, running losses, and spitback.

Evaporative emissions are regulated for the useful life of the vehicle and separately for two vehicle classes, light HDVs and heavy HDVs. However, evaporative emissions for diesel engines are relatively low due to the low volatility of the fuel. Therefore, the EPA standards are applicable to heavy-duty gasoline, methanol, LPG, and natural gas fueled engines. Beginning with model year 1998 engines, emissions standards were also developed for entire heavy-duty engine fleets of low emission vehicles (LEV) as sold by engine manufacturers (Figure 3-2). The pollutants regulated for the engine fleet standards are CO, NMHC+NO_x, PM, and formaldehyde (HCHO).

Most of the available engine performance data come from the data bank generated by the Environmental Protection Agency (EPA) as a result of the vehicle emissions certification procedure (Guensler et al, 1991). These data are the results of chassis dynamometer testing (vehicle testing in laboratories) during specified driving cycles. Two cycles are used in these tests: the Federal Test Procedure (FTP) and the Fuel Economy Test (FET). The FET is used to obtain the fuel economy figures reported in annual EPA mileage guidelines and to measure exhaust emissions. The FTP cycle was designed to approximate urban driving conditions.

The accuracy of this approach to collecting engine performance data is limited by the use of steady state operating data to predict transient behavior. Emissions are measured during the FTP. There are difficulties in the measurement of hydrocarbons for emission certification (some are counted twice: once in gaseous form and once in particulate form). However, the FTP estimates of emissions have historically been found to be the most accurate easily reproducible engine emissions estimator.

The models developed in this research will be incorporated into a heavy-duty vehicle emission estimation process based on engine load rather than fuel economy. As described earlier, using engine load provides a more sound theoretical basis for estimating heavy-duty vehicle emissions than current modeling techniques.

Emission Category	CO (g/bhp-hr)	NMHC + NO_x (g/bhp-hr)	PM (g/bhp-hr)	HCHO (g/bhp-hr)
LEV (Fed. Fuel)	n/a	3.8	n/a	n/a
LEV (CA Fuel)	n/a	3.5	n/a	n/a
Inherently LEV	14.4	2.5	n/a	0.050
Ultra LEV	7.2	2.5	0.05	0.025
Zero Emission Vehicle	0	0	0	0

Figure 3-2: Federal EPA Emissions Standards for Heavy-Duty LEVs

3.6 Current Emissions Modeling Regime

3.6.1 Emission Inventory Modeling

Mobile source emissions are estimated by coupling vehicle activities with corresponding emission rates. The emissions calculated from each activity are then summed to generate the total emission inventory. For modeling purposes, regulatory agencies currently define four diesel-related specific activity types for which emission rates can be directly applied: running emissions, hot starts, cold starts, and engine idling. To estimate the magnitude of the activities, estimates are generally derived for the following variables: number of vehicles, number of trips, vehicle-miles traveled, and hours of idling.

The general procedure for developing emission-producing heavy-duty vehicle activity estimates is to first generate fleet mix estimates through some combination of local, regional, and national truck registration data. Then the number of trips is estimated by developing trip rate estimates for each of the truck classifications in the overall truck fleet. Trip rates are generated based on either truck count data or commercial vehicle surveys. Estimates of vehicle miles traveled are determined through surveys and/or truck counts to determine the running emissions of the heavy-duty truck fleet. Engine idling, along with vehicle starts, are two important emission factors which are currently not included in truck emissions models.

Therefore, heavy-duty diesel emissions models must include vehicle activity estimates, vehicle fleet estimates, and emission rate estimates. Historically, for heavy-duty truck activity, many surrogate indicators (such as traffic counts) have been used to generate estimates as opposed to the four-step travel demand models used for light-duty vehicles. Due to the relatively high use of these surrogate variables, only the use of vehicle miles traveled is currently used in estimating the heavy-duty diesel emissions inventories in most metropolitan areas.

The use of traffic counts as a surrogate for VMT is one source of uncertainty for these heavy-duty truck emissions estimates. These counts are usually based on HPMS data that have been shown to be highly inaccurate based on several factors (Sharma et al, 1996):

1. inadequate number of permanent counting sites,
2. mis-classification of roadways,
3. numerous assumed and estimated counts,
4. infrequent sampling periods, and
5. questionable axle count conversion algorithms into VMT.

However, in the past ten years a handful of metropolitan areas including Atlanta have developed commercial vehicle and truck surveys which incorporate heavy-duty vehicles to varying degrees. Travel demand models developed from the data in these surveys will allow for more accurate estimates of truck VMT and the inclusion of hot starts, cold starts, and idling into heavy-duty vehicle emissions models.

Current vehicle emission rates are estimated through laboratory testing, using the methods and procedures specified by the U.S. EPA. Emission rates for heavy-duty diesel engines are determined first for each truck engine classification. The U.S. EPA has defined three broad classifications of heavy-duty vehicles: light heavy-duty, medium heavy-duty, and heavy heavy-duty trucks (Guensler et al, 1991). These three classifications were originally developed to correspond loosely to engine horsepower rating differences and variation in vehicle usage for subclasses of trucks in the overall truck fleet. In the past 15 years, technological advances have allowed for truck engine manufacturers to increase the rated horsepower of most heavy-duty engines so that new horsepower rating classifications will likely be required for each of the truck engine classifications listed below.

Light heavy-duty diesel engines are rated between 150 and 250 horsepower. The vehicle types originally intended for this classification include vans, recreational vehicles, and some single axle straight trucks. The gross vehicle weight rating (GVWR) of these vehicles is typically less than 19,500 pounds (40CFR86.085-2(a) (1)). Light heavy-duty engines are generally not designed for rebuild.

Medium heavy-duty diesel engines are rated between 250 to 350 horsepower. Vehicle types originally intended for this classification include buses, small tandem axle trucks, small dump trucks, etc. The GVWR of a medium heavy-duty vehicle is usually between 19,500 to 33,000 pounds. (40CFR86.085-2(a) (2)). Medium heavy-duty diesel engines may be sleeved and may be designed for rebuild. Heavy heavy-duty diesel engines exceed 300 horsepower and were originally intended to include tractor-trailer combinations, trucks and buses used in long haul operations. The GVWR for these vehicles typically exceeds 33,000 pounds (40CFR86.085-2(a) (3)). Heavy heavy-duty diesel engines are sleeved and designed for multiple rebuilds.

Emission rate correction factors are utilized to account for the influence of the operating environment on the vehicle. For example, a diesel engine has a relatively long warm-up period due to the low volatility of diesel fuel. Therefore, there will be differences between the running emissions of a heavy-duty diesel vehicle in cold start as opposed to hot start. Other factors such as vehicle speed and operating temperature can also affect emission rates. Baseline emission rates are determined from standard test procedures, and are applied to specific operating conditions using adjustments established through the use of laboratory determined correction factors.

3.6.2 Inadequacies of the Current Modeling Regime

The heavy-duty vehicle emission inventory is estimated by combining the activity estimates that are based on surrogate measures with the estimates of emissions rates adjusted using emission correction factors. The sources of uncertainty in the present emissions modeling regime for heavy-duty vehicles can be divided into four major categories (Guensler et al, 1991):

- heavy-duty vehicle activity estimates,
- emission rates and correction factors,
- spatial and temporal resolution, and
- analysis of emission reduction strategies.

The use of surrogates to estimate actual vehicle activity is a major source of uncertainty of heavy-duty emissions estimating. Heavy-duty vehicle activities are generally not estimated with the trip generation and distribution models that are used for passenger automobiles. Instead highly aggregated truck counts based on average speed estimates are utilized to estimate total heavy-duty VMT. The aggregation of questionable surrogate estimates to obtain overall vehicle miles travel estimates is a fundamental source of uncertainty in heavy-duty emissions estimates. Implementation of comprehensive goods movement models capable of generating temporally and spatially complete trip estimates are necessary to develop VMT estimates with the accuracy currently available for passenger cars.

Vehicle activities omitted from current heavy-duty emission models include number of idling activities, distribution of idling duration, and the number and distribution of engine starts. In addition, the current average speed models used for both passenger car and heavy-duty vehicle emissions estimation are less accurate than emissions estimations based on both speed and acceleration activities.

The current estimates of emission rates and correction factors for heavy-duty vehicles have many interrelated factors adding to the uncertainty of heavy-duty emission estimates. First, there is the uncertainty associated with the original test method due to problems of accuracy and precision based on the limited number of heavy-duty vehicles included in the test sample. Second, there are model inadequacies based on the lack of representation of the entire diesel engine fleet (engine size and power) and the entire heavy-duty vehicle fleet (truck size and load) in the original test engines. There are also a number of unresolved questions revolving around the conversion factors used to translate from g/bhp-hr to g/mi. emission rates. The failure to include certain activities, such as idling and acceleration, in the determination of aggregate emission rates and conversion factors also creates an additional uncertainty in the overall estimates, because the effects of these activities are not incorporated into the heavy-duty vehicle estimates.

The present lack of spatial and temporal distribution of vehicle activities is an additional source of uncertainty in heavy-duty emissions models. Point sources of vehicle activities such as roads with steep grades, truckstops, and diesel refueling stations are not included in current heavy-duty vehicle activity models. High levels of aggregation of vehicle activities also limit the ability of present models to differentiate between locations with potentially different temporal characteristics such as retail areas, industrial areas, and residential areas.

3.7 The MEASURE Model

The Georgia Tech Research Partnership has developed the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE) model in cooperation with a number of research partners including the U.S. EPA and the Federal Highway Administration. MEASURE estimates mobile source emissions as a function of engine and vehicle operating modes such as acceleration, deceleration, cruise, idle, and power demand. 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 significantly reduced. Unexplained variability still exists in the MEASURE model, but the framework is capable of providing significant enhancements over the current average speed modeling regime (Guensler et al., 1997).

The primary objectives of the MEASURE model include:

- the development of emissions relationships that improve emission inventory modeling techniques and include explicit effects of vehicle fleet characteristics, vehicle operating conditions, and driver behavior,
- the development of emission factors appropriate to each modal emission-producing activity (with specified certainty),
- the inclusion of traffic flow parameters in the vehicle activity estimation process,
- the explicit incorporation of the effects of various policy initiatives and programs on fleet emissions (e.g. effects of inspection and maintenance and repair programs),
- the development of a model that is sensitive to the changes in vehicle technologies, fuels, and traffic flow,
- the estimation of gridded hourly activity and activity attribute data (with specified certainty), and
- the validation of emission estimates from new emission inventory models.

Figure 3-3 shows the conceptual framework governing the MEASURE model. For the transportation network, vehicle fleet is estimated by link and zone. For off-network activity, the vehicle fleet is estimated by zone. For each vehicle sub-fleet, vehicle activity profiles are estimated in terms of the distributions of emission-related operating, driver, and environmental conditions. These profiles are combined with sub-fleet specific emission rate relationships for each operating characteristic distribution to estimate emissions for each link and mini-zone.

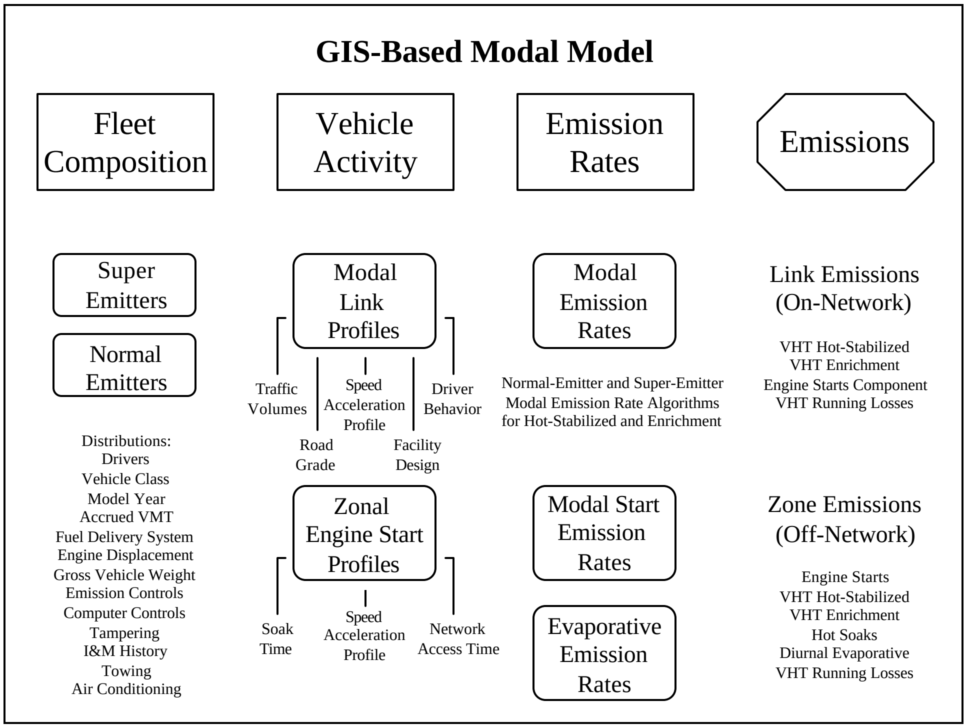


Figure 3-3: Conceptual Model for the Development of a New Emissions Model (Bachman et al., 1995)

The emissions model is developed for use on a geographic information system (GIS) platform. The use of a GIS system allows for the incorporation of spatial and temporal attributes of the network with a wide variety of data sources. 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 (Bachman, 1997).

In the MEASURE model, heavy-duty vehicles are classified based on engine horsepower categories. For a particular heavy-duty engine category, emissions rates are assumed to be constant for a given engine load. Instantaneous engine loads are estimated through the incorporation of numerous variables including vehicle weight, speed, acceleration, and grade. The purpose of this research is to generate estimates of onroad horsepower and weight distributions based on an axle-trailer vehicle classification scheme. The research will be used to develop the heavy-duty vehicle activity and fleet characteristics portions of the MEASURE model.

CHAPTER IV

4. CONTRIBUTIONS TO THE LITERATURE

The relationships examined in this research will establish links between important variables for modal emissions estimation of heavy-duty vehicles. The following topics will be documented in detail significantly improving upon existing heavy-duty vehicle research:

- the relationship between truck classification and gross vehicle weight,
- the relationship between truck classification and engine horsepower,
- the relationship between truck engine horsepower and gross vehicle weight, and
- the establishment of a heavy-duty vehicle classification methodology appropriate for characterizing the heavy-duty vehicle weight/horsepower relationship.

4.1 Relationship Between Truck Class and GVW

4.1.1 Contribution to Existing Data

The assumptions of this study build on the results of a New York metropolitan truck survey that indicated that heavy-duty truck data collected in several different locations had a similar weight distribution at each location (Wegmann, 1995). To verify this assumption, weight data were collected at several locations throughout the Atlanta metropolitan area to determine the spatial uniformity of heavy-duty vehicle weight distributions. It is important to note that if the weight distributions exhibited spatial variability, then a much more complex model which likely incorporates goods movement by commodity type and land use as causal variables would likely be necessary to enable prediction of heavy-duty vehicle weight distributions.

Current heavy-duty vehicle databases have assumed that weight distributions are uniform throughout large urban areas for vehicles of each vehicle classification (Blower et al., 1988; Dahlin, 1992). The data collected in this research will determine the validity of this assumption for the Atlanta metropolitan area. Additionally, this research will supplement existing weight distributions by determining the extent of temporal variation in weight distributions for each of the heavy-duty vehicle classifications. Existing research has documented the variation in commodity movements by hour (Blower et al., 1988 and Lau, 1995), and existing vehicle count data has confirmed the variability of truck volumes on a hourly basis. The combination of these factors along with the time-varying cost of truck drivers likely result in temporal distribution of heavy-duty vehicles that carry heavier loads at night and more empty vehicles during the day.

4.1.2 Contribution to Modal Emissions Modeling

As outlined in Chapter 3, the establishment of the temporal variation in gross vehicle weight distributions is crucial for the development of the heavy-duty vehicle portion of the modal emissions model. Emissions models by nature generate time-specific outputs. Therefore, the data inputs into these models must also be sensitive to the variation in the data relative to temporal characteristics. The development of vehicle weight distributions based on hourly categories relevant for both emissions modeling and truck activity is an important database to complete.

Examination of the relationship between location and GVW is an important contribution of this research. Spatially variable weight distributions would require much more sophisticated models than those developed through this data collection effort. Verification of weight distributions as uniform throughout the metropolitan area allows for the development of a single weight distribution for each temporally relevant period.

4.1.3 Contribution to Pavement Management Planning

The axle loads of heavy trucks contribute to various forms of pavement distress. Of the various types of damage, fatigue (which leads to cracking) and permanent deformation (rutting) are of great importance. The amount of rutting of the asphalt concrete layer is directly dependent on the sum of the gross vehicle weight of all vehicles utilizing the roadway. However, fatigue damage is dominated by the most heavily-loaded axles. The most significant axle for road damage is the heavily-loaded conventional tire on steer axles. Elevated temperatures also increase fatigue and rutting in pavements.

Therefore, a thorough understanding of the relationship between truck classification and gross vehicle weight will also serve to generate more accurate estimates of pavement damage. In turn these more accurate estimates will serve to guide management strategies for road maintenance. Truck size and weight limits are usually based on pavement damage estimates. The efficiency of these regulations will also be more accurately measured with more accurate truck weight distribution models. Additionally, the relationship between temperature and pavement damage indicates that the inclusion of temporal factors in the data collected in this research can assist in pavement damage estimation.

4.2 Relationship Between Truck Class and Engine HP

4.2.1 Contribution to Existing Data

The data relating truck classification to engine horsepower can be extracted from vehicle registration lists based on vehicle identification numbers and truck manufacturer records. Ideally, the data collected as part of existing commercial vehicle surveys could be used to determine this relationship. Unfortunately, the VINs of most surveys (including the Atlanta commercial vehicle survey) are either neglected, inaccurate, or incomplete due to inadequacies of survey instruments and errors by survey participants. For the few commercial vehicle survey data sets with complete VIN data, the process of extracting engine horsepower has not been performed.

This research will develop relationships between truck classification and engine horsepower by heavy-duty vehicle classification based on roadside surveys. This will be more representative of the onroad truck fleet than engine horsepower extracted from the aforementioned extraction of horsepower from existing surveys, because the roadside surveys will be based on actual truck fleets rather than vehicles in a particular registration database.

4.2.2 Contribution to HDV Emissions Modeling

The relationship between truck classification to horsepower is important for HDV emissions modeling for a number of key reasons. The engines sampled as part of the EPA engine testing procedures are based on existing relationships between heavy-duty vehicle class and engine horsepower. A representative sample from each of the horsepower categories is tested to develop the emission rate factors. However, engine technology has changed rapidly in the past ten years, and the data for which the testing procedure has been developed no longer reflects the overall onroad vehicle population. Engine horsepower has increased significantly partly due to increases in truck size and weight limits and partly due to the desire to provide increased comfort for truck drivers for all operating conditions. Therefore, continuously updated vehicle class and horsepower data are important to maintain a strong correlation between the engines tested by the EPA and the onroad vehicle fleet.

For modal emissions modeling the relationship between truck classification and horsepower is important, because the horsepower determines the speed-gradeability of the overall truck. The horsepower of a truck can be compared to the load conditions on the vehicle to determine the percent of time spent in various load conditions. The load on the engine can be categorized into three factors: wind resistance, grade resistance, and inertial resistance forces as discussed in Chapter 2. However, a 500 HP engine will have different performance and therefore different emissions characteristics than a 350 HP engine when loaded under the same conditions. The 500 HP engine will operate much less frequently at the maximum power conditions that result in increased emissions of certain pollutants.

4.3 Relationship Between Engine HP and GVW

4.3.1 Contribution to Existing Data

There are currently no data directly relating engine horsepower and onroad gross vehicle weight. Indirect inferences can be made based on the limited existing data for truck horsepower distributions and gross vehicle weight ratings from vehicle registration data combined with the questionable accuracy of existing truck weight data from weigh-in-motion equipment. This research explicitly surveys vehicles for engine horsepower and onroad gross vehicle weight. There is one survey data set collected by the University of Michigan Transportation Research Institute (UMTRI) which explicitly incorporates onroad vehicle weight for a large data set (Blower et al, 1988). However, the gross vehicle weight was based on operator estimates not from actual scales. Therefore, the accuracy of this weight data are unverifiable. In addition, the horsepower data for this data set are also based on truck operator estimate and not extracted from the VINs. This creates an additional level of uncertainty for estimating the engine horsepower of the truck fleet included in the UMTRI sample.

The research in this dissertation establishes the relationship between gross vehicle weight and horsepower explicitly for a large set of individual vehicles. In addition, some data are collected for each of a number of vehicle classes to determine the differences between engine horsepower across specific portions of the vehicle fleet. This data collection process is necessary for developing horsepower and gross vehicle weight distributions for the full range of heavy-duty vehicle fleet mixes. Collecting this data based on heavy-duty vehicle class is also a first step at establishing criteria for comparing truck characteristics on different road classifications.

4.3.2 Contribution to HDV Emissions Modeling

The relationship between engine horsepower and onroad gross vehicle weight can be utilized to create more accurate loading conditions for the EPA heavy-duty vehicle testing procedure. The EPA tests vehicle engines based on estimated onroad loading conditions. These loading conditions are based on the estimated internal and external resistance forces of the vehicle. For heavy-duty vehicles, gross vehicle weight can vary by magnitudes of almost three depending on whether the vehicle is empty or full. Therefore, understanding the relationship between the gross vehicle weight and engine horsepower is important.

The key issue is the establishment of the relationship between loading of the truck and the horsepower of the truck. For a particular heavy-duty vehicle classification, it is important to establish whether empty trucks have a different horsepower distribution than full trucks of the same classification. The existence of a class-specific engine horsepower and gross vehicle weight relationship will determine the necessity of the EPA developing detailed engine emission rate testing results for certain engine horsepower under particular engine loading conditions.

For example, if for a particular classification of trucks 500 HP engines are found to be correlated with full trucks, and for the same classification 350 HP engines are found to be correlated with empty trucks, then the EPA could test 500 HP engines at higher loading conditions and 350 HP engines at lower loading conditions. If no statistical relationship between gross vehicle weight and engine horsepower exists, then engines can be tested based purely on the shape of the gross vehicle weight distribution.

4.4 Vehicle Classification Methodology

4.4.1 Contribution to Existing Vehicle Classification

This research will develop a specific vehicle classification format that can be utilized to simultaneously measure the three fundamental relationships: 1) class vs. GVW, 2) class vs. HP, and 3) GVW vs. HP for each vehicle class. As mentioned in Chapter 2, there are several different vehicle classification systems that have been developed. Choosing a vehicle classification system for most traffic studies depends on the capabilities of the data collection device used, the overall vehicle fleet mix, and the purpose of the traffic study. The majority of vehicle classification systems are based on either axle-trailer configurations or gross vehicle weight ratings. The vehicle classification method developed in this study is based on axle-trailer configurations, because this classification method is used by the portable WIMs which collect the weight data and this classification can be implemented for the roadside truck surveys. The final classification scheme will necessarily have the following specific characteristics:

- compatibility with the FHWA 16-vehicle classification scheme,
- specific classes only in the case of differentiation between GVW and/or HP distributions, and

- class structure easily identifiable during manual or automated roadside traffic count/classification programs.

The final classification scheme will contain as few classes as are necessary to differentiate between vehicle groupings with different characteristics.

4.4.2 Contribution to HDV Count/Classification Programs

This classification scheme will create a simple structure through which HDV count and classification programs can be implemented for emissions modeling purposes. The final scheme will be more compact than the 16-vehicle FHWA scheme. A simplified scheme will allow for less resources to be used during emissions-related traffic count and classification programs, because less data are needed to obtain sufficient counts to develop estimates with the desired confidence bands for each vehicle class.

The final classification scheme will incorporate more variables than the oversimplified 2-vehicle truck class system (single-unit and combination) often incorporated into existing vehicle count programs. These simplified heavy-duty vehicle classification methods often do not account for the differences in activity and vehicle characteristics for vehicle classes within this 2-vehicle classification. For example, 2-axle single-unit trucks are most often used for short trips of dry goods, whereas 3-axle single-unit trucks are often used for hauling loose materials in open-top containers with much heavier shipments and with vastly different origin-destination patterns. Additionally, 3-axle combination trucks are often used for local trips of goods from break-bulk terminals, as opposed to the 5-axle combination trucks that are more often used for inter-city trips between major terminals.

4.4.3 Contribution to HDV and Commercial Vehicle Survey Methodology

The establishment of a classification structure that efficiently measures the relationship between heavy-duty vehicle classification, GVW, and HP can be incorporated into heavy-duty and commercial vehicle surveys to allow for broader utilization of the data collected in these surveys. The majority of these surveys use only the weight rating of the vehicle as the classification basis for generating survey samples. The corresponding relationships developed between the overall truck fleet and various activities in the truck forecasting process such as trip generation, trip distribution, and route choice are limited to representativeness to GVWR classes.

By using the axle-trailer classification scheme developed in this research as an additional data item in the survey process, the data collected can be directly included in a heavy-duty vehicle emissions model for more accurate VMT estimates. In turn these surveys can serve as important indicators of activity levels for the emission-relevant activities of truck emissions models. The axle-trailer classification scheme will also allow for the incorporation of commercial vehicle survey data into established equivalent single axle load (ESAL) computations to assist in pavement management.

4.4.4 Contribution to HDV Emissions Modeling

Currently, the EPA utilizes a heavy-duty vehicle classification structure based solely on gross vehicle weight ratings. This is an efficient method of characterizing the truck fleet based on an estimated load range for the vehicle. Using this method, the engine characterized as belonging to a particular vehicle classification can be tested at loading conditions up to its maximum rated weight. However, it is often difficult to translate the GVWR classification structure to the truck data contained in the existing truck count and classification programs.

This research will develop a complimentary classification structure that can be applied directly either to a truck classification scheme based solely on axle-trailer configurations or horsepower distributions. In this manner, the classification structure will be compatible to both the EPA method and the existing truck count and classification method.

4.5 Supplemental Contributions

The paucity of relevant truck data for metropolitan-level goods movement has created data gaps between the relationships of numerous heavy-duty vehicle variables relating vehicle characteristics and activity. Both the roadside surveys and the portable WIM equipment data collection processes allow for the collection of supplemental variables to test against the three variables of primary concern (class, GVW, and HP).

4.5.1 Supplemental Contributions from Roadside Surveys

Roadside truck surveys are limited in the amount of data items collected per vehicle to minimize the stop time for time-sensitive trucks. Therefore, while conducting roadside surveys with information collected verbally from the truck driver, additional data are collected whenever possible. The additional data collected as part of this research included origin, destination, driver estimate of HP, truck body type, and truck company type. The collection of the truck VIN also allows for the accumulation of vehicle characteristic data other than simply manufacturer specified horsepower. The VIN provides information such as model year of the truck, cab style, and gross vehicle weight rating. As detailed later in this research, the incorporation of the model year as a data collection item was surprisingly important.

4.5.2 Supplemental Contributions from Portable WIMs

The use of portable WIM equipment allowed for the collection of gross vehicle weights for a range of vehicle classifications for all hourly and daily temporal periods. Vehicle length and vehicle speed are two supplemental variables which are electronically included for each vehicle record. Future research should examine the relationship between these variables compared with gross vehicle weight and vehicle classification. The supplemental data are tested separately from the three fundamental variables of this research and will be included in the model where relevant.

CHAPTER V

5. PRELIMINARY TRUCK SURVEY RESULTS

Preliminary truck surveys were conducted at a Georgia weight enforcement station to establish an appropriate classification scheme for the development of weight and horsepower distributions. The surveys were also used to statistically determine the relationship between truck weight and engine horsepower for each truck classification.

5.1 Development of Classification Scheme

Tractor-trailer configuration was selected as the classification scheme for this research rather than gross vehicle weight rating. Use of a tractor-trailer classification method allows a single system to identify vehicles for both the portable WIM equipment data and roadside truck surveys. Under the Federal Highway Administration (FHWA) vehicle classification system, there are ten different classes of trucks based on various tractor-trailer classifications. Interstate vehicle counts indicate that a few of the classes are a large percentage of the overall truck fleet. Figure 5-1 shows the percent of trucks in each of the FHWA truck classes from data collected from the Georgia Department of Transportation (GDOT) Highway Performance Monitoring System (HPMS) on Interstates outside of the perimeter freeway in the 13 county Atlanta metropolitan area. The table shows that 5-axle, 2-unit trucks dominate the Interstate truck traffic and further indicates that the 2-axle, 1-unit trucks combined with the 5-axle, 2-unit trucks comprise approximately 90% percent of the truck volume.

FHWA Classification	Number of Axles	Number of Units	Percent of Truck Total at Typical HPMS Interstate Site
7	2	1	10-20%
8	3	1	3-5%
9	4	1	Less than 1%
10	3	2	1-3%
11	4	2	1-3%
12	5	2	65-75%
13	6	2	3-5%
14	5	3	3-5%
15	6	3	Less than 1%
16	7	3	Less than 1%

Figure 5-1: FHWA Truck Classifications and Georgia Truck Count Percentages

Using the FHWA classification as a base, a modified classification system was developed for the survey at the weigh station that would ensure that all truck classifications were covered, and that a significant number of each of the vehicle types could be collected in the survey. The ten FHWA truck classes were combined into four classes based on similarities in truck design. The four classes (and notation used through the remainder of this paper) are:

- 2-axle, 1-unit trucks (noted as Class 5 trucks)
- 3 or more axle, 1-unit trucks (noted as Class 6,7 trucks)
- 3 or 4 axle, 2-unit trucks (noted as Class 8 trucks)
- 5 or more axle, 2 or more unit trucks (noted as Class 9-13 trucks)

The number of samples collected for each of the four truck classifications is based on the percent of trucks in that class that were observed from actual truck counts. The truck surveys were conducted at the Douglas County weigh station which is located approximately 15 miles west of downtown Atlanta on the eastbound side of Interstate-20 which runs east-west through the Atlanta metropolitan area. Six surveys were conducted between the period of December 1996 and April 1997 on weekdays during the daytime hours. These time periods were selected because they are the most relevant for the overall emissions modeling purposes. Additionally, the operating hours of the weigh station are generally confined to the daytime on weekdays.

The weigh station officer selected trucks for the survey from the traffic stream based on the availability of surveyors. The weight of the trucks selected for the survey was recorded using the stationary scale at the weigh station. The weigh station officer then directed the truck into the truck parking lot where the vehicle identification number, body type, and origin-destination information for each truck were collected.

The vehicle identification numbers (VINs) for heavy-duty trucks is generally located on the inside of the driver-side door panel of the truck. For vehicles that did not have VINs on the inside of the driver-side door, the VIN was obtained from the vehicle registration. Body type data were also collected and divided into four categories: dry container, tanker, tow (trucks that pull other vehicles), and flatbed trucks. Origin-destination information was requested verbally from the driver and was generally recorded by city if within the state of Georgia or by state if outside the state of Georgia. The origin-destination data were collected for the last five of the six weigh station surveys. All of the truck data were recorded manually onto survey forms and later transferred to an electronic spreadsheet. A truck survey form is included in Appendix C.

Additional truck data were collected from the records of the Douglas County weigh station overweight truck database during the week of March 30, 1997. The overweight truck database includes all vehicles that were fined for traveling at weights over the legal limit of the State of Georgia. For each overweight truck the data recorded in the weigh station files include VIN, truck company, gross vehicle weight, and origin-destination information based on city if in the state of Georgia and state if outside the state of Georgia. This is the only historical data collected at the Georgia weigh station. The overweight truck sample included in the preliminary data were collected for 43 trucks, 41 of which were Class 9-13 trucks, and two of which were Class 6,7 trucks.

5.2 Preliminary Surveys Results

5.2.1 Surveys Findings

Two truck VIN decoding books (Truck Index, 1996 and Stanton, 1996) provided important characteristics of the surveyed trucks. For the majority of the vehicles, the VIN decoding book contained data on truck or cab style, cab manufacturer and model, engine manufacturer and model, gross vehicle weight rating (GVWR), axle configuration, type of brakes, the year of manufacture, and the assembly plant location. However, for most of the trucks, the VIN book either lacked horsepower data or provided horsepower ranges. Specific horsepower values are needed to perform statistical analysis on the engine horsepower data; horsepower ranges are inadequate.

Therefore, the dealers of the various truck manufacturers were directly contacted to acquire truck horsepower ratings for most of the surveyed vehicles. Dealer databases contain specific horsepower information based on rating at time of manufacture for each truck. Trucks are traced throughout the dealers' records using VINs that can be easily matched to the surveyed data. However, data for approximately one-third of the vehicles were not traceable in the dealers' computer systems for various reasons. It is possible that the VINs from these vehicles were recorded improperly during the survey or that the truck dealer database was either malfunctioning, incomplete, or not recently updated.

A total of 157 out of 221 trucks were successfully decoded to the level where precise truck horsepower ratings were determined. The Class 9-13 truck class had the lowest decoding success rate of 68.4% compared to the other classes which ranged from 78.3%-90.0%. This discrepancy is due primarily to a few of the large truck manufacturers which had particularly bad truck databases. Figure 5-2 shows the successful horsepower data retrieval for each of the truck classes. The Class 9-13 (svy) class represents the Class 9-13 truck data that were collected from the onroad survey, while the overweight class represents the truck data that was collected using the weigh station overweight database.

Truck Class	Sample No. Collected	Horsepower Ratings Determined	Decoding Success Rate
Class 5	40	35	87.5%
Class 6,7	23	18	78.3%
Class 8	20	18	90.0%
Class 9-13 (svy)	95	65	68.4%
Overweight	43	31	72.1%
Total	221	157	71.0%

Figure 5-2 Successful Horsepower Determination from Preliminary Surveys

As expected, the results show that the larger truck classifications have a higher average horsepower than the smaller truck classifications. Figures 5-3 shows the distributions of horsepower ratings for each of the four truck classes based on horsepower bins of 50 units.

The Class 9-13 truck classifications averaged significantly higher horsepower ratings of about 370, relative to the Class 8, Class 6-7, and Class 5 truck classes that averaged horsepower ratings of 293, 279, and 188 horsepower respectively.

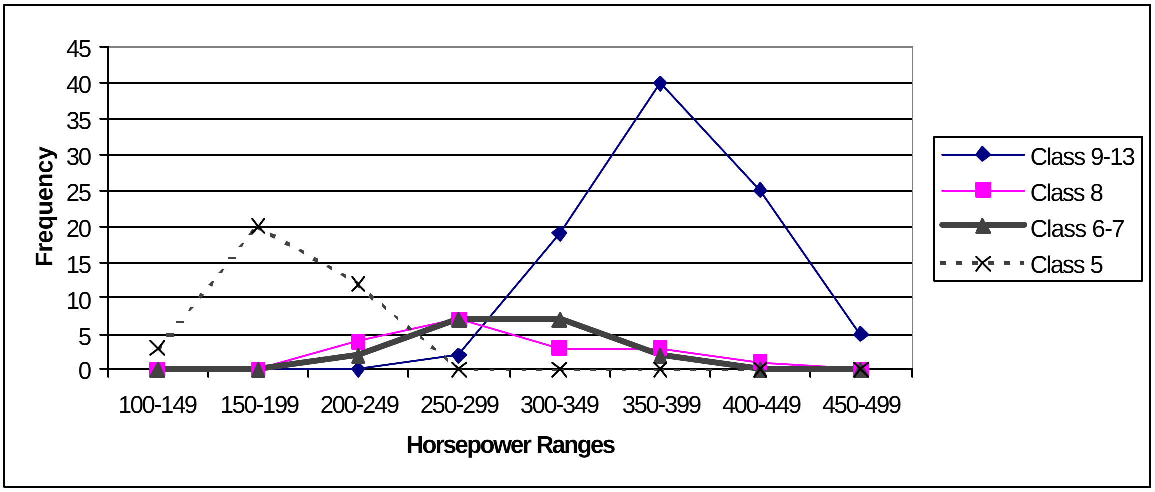


Figure 5-3: Horsepower Distributions by Class for Preliminary Surveys

5.2.2 Testing the Relationship between Horsepower and Truck Weight

5.2.2.1 Horsepower-Weight Relationship for All Trucks

Figure 5-4 shows a scatterplot of the horsepower and the total truck weight for all of the trucks in the six Douglas County weigh station surveys. A crosstab analysis was performed on the horsepower/weight data to determine if there is a statistical relationship between the weight and the horsepower ratings of trucks. Crosstab analysis can be used when two different quantities are measured on each item in a sample to determine the degree of association or correlation between them (Cohen, 1991). Figure 5-5 shows the contingency table of horsepower ranges and weight ranges for the sample. The 157 trucks have been cross-classified according to the two attributes ‘weight’ and ‘horsepower’. This analysis will test whether the weight bins are independent of horsepower bins.

In practical terms, this statistical test determines if there is a tendency for heavier trucks to have a higher horsepower rating than light trucks. The null hypothesis is the assumption that there is no association between truck weight and truck horsepower. That is, vehicles and loads are not paired purposely and loads are randomly assigned to cabs and cargo units irrespective of engine power. If the null hypothesis were true than each bin would have proportionately equal observation level as other bins based on the row and column total for the individual cell.

As an example of a true null hypothesis, if 20% of the trucks within the horsepower range of 200-299 are between the weights of 40,000 and 59,999 pounds, then 20% of the trucks within the horsepower range of 300-399 should also be between the weights of 40,000 and 59,999 pounds. The lower the deviation between the percentages of different weight and horsepower bins, the more likely the null hypothesis is true.

The expected frequencies of the contingency table are calculated for each cross-classification if the null hypothesis were true. Figure 5-5 shows the observed and expected values for each cross-classification bin. The values recorded from the survey are shown without parentheses. The values inside the parentheses represent the expected value, if there was no relationship between horsepower and weight.

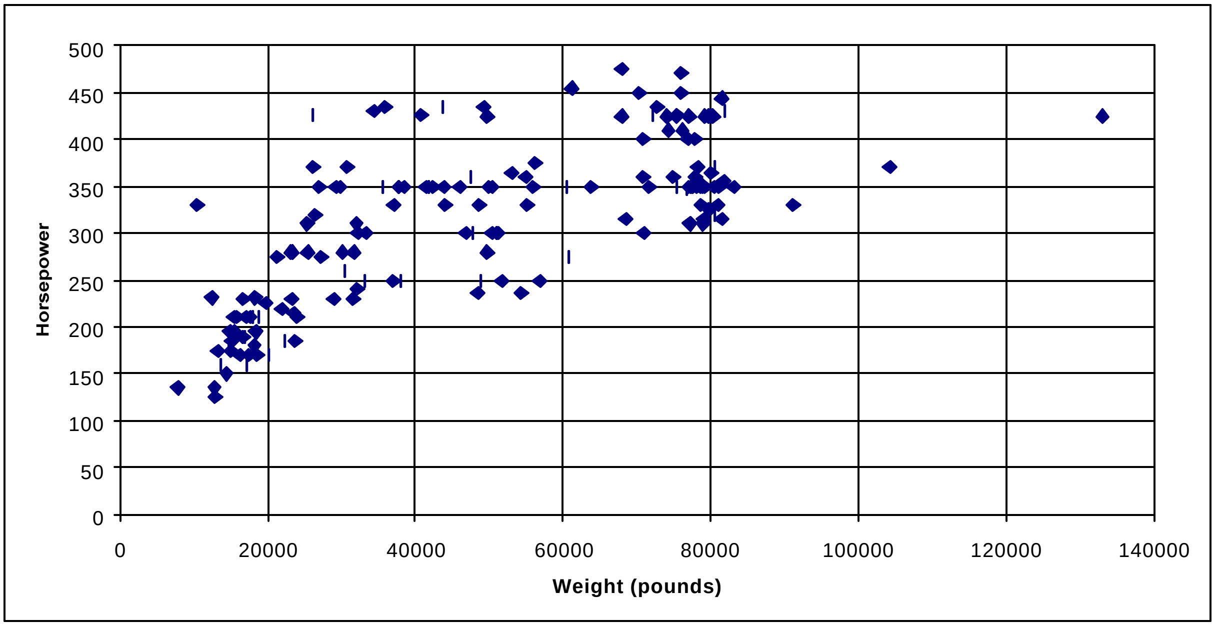


Figure 5-4: Scatterplot of Horsepower and Weight for all Trucks for Preliminary Surveys

	Truck Weight Ranges in 20,000 lb. bins				
Horsepower Range	0 - 19,999 lb.	20,000-39,999 lb.	40,000-59,999 lb.	60,000-79,999 lb.	80,000 lb. and over
100-199	20 (4.3)	3 (5.6)	0 (4.5)	0 (6.6)	0 (2.1)
200-299	10 (6.8)	19 (8.7)	6 (7.0)	1 (10.3)	0 (3.3)
300-399	1 (14.1)	15 (18.2)	22 (14.5)	26 (21.4)	11 (6.8)
400-499	0 (5.8)	3 (7.5)	4 (6)	20 (8.8)	4 (2.8)

Figure 5-5: Expected and Observed Values for Horsepower and Truck Weight Ranges for Preliminary Surveys

To compute the expected frequency for trucks weighing 60,000-79,999 pounds with horsepower ratings between 300 and 399, the following operation is performed. Multiply the total number of trucks weighing 60,0010-79,999 pounds by the total number of trucks with horsepower ratings between 300 and 399, then divide by the total number of trucks in the sample, or (47*75)/157, which is 21.4. Expected frequencies for other bins are calculated in the same manner.

The observed and expected frequencies can now be checked for similarity with the χ^2 goodness-of-fit test. For each of the 20 cross-classifications, the contribution to the χ^2 test value equals the square of the difference between the observed and expected frequencies divided by the expected frequency. Applying this procedure to the truck data:

$$\chi^2 = (20-4.3)^2/4.3 + (3-5.6)^2/5.6 + (0-4.5)^2/4.5 + \dots + (4-2.8)^2/2.8 = 141.07 \qquad (5\text{-}1)$$

The 1% significance value of the χ^2 distribution for 12 degrees of freedom is 26.22. We can therefore conclude that there is a strong relationship between the weight of a truck and the horsepower of the truck for the entire truck fleet. This is important because it indicates that horsepower and vehicle weight can not be analyzed independently for the entire truck fleet in the heavy-duty vehicle portion of the load-based emission model.

5.2.2.2 Weight-Horsepower Relationship by Truck Classification

Scatterplots of the weight-horsepower relationship for each of the four classes of trucks are shown in Figures 5-6 to 5-9. The lack of any pattern in the four scatterplots indicates that for each of the four classifications there is no relationship between weight and horsepower. Crosstab analyses were used to statistically confirm the lack or relationship between truck weight and engine horsepower for each truck class, similar to the analysis performed for the entire truck fleet. In other words, empty 5-axle trucks have the same horsepower distribution as 5-axle trucks that are full. This result is true for each of the four truck classifications.

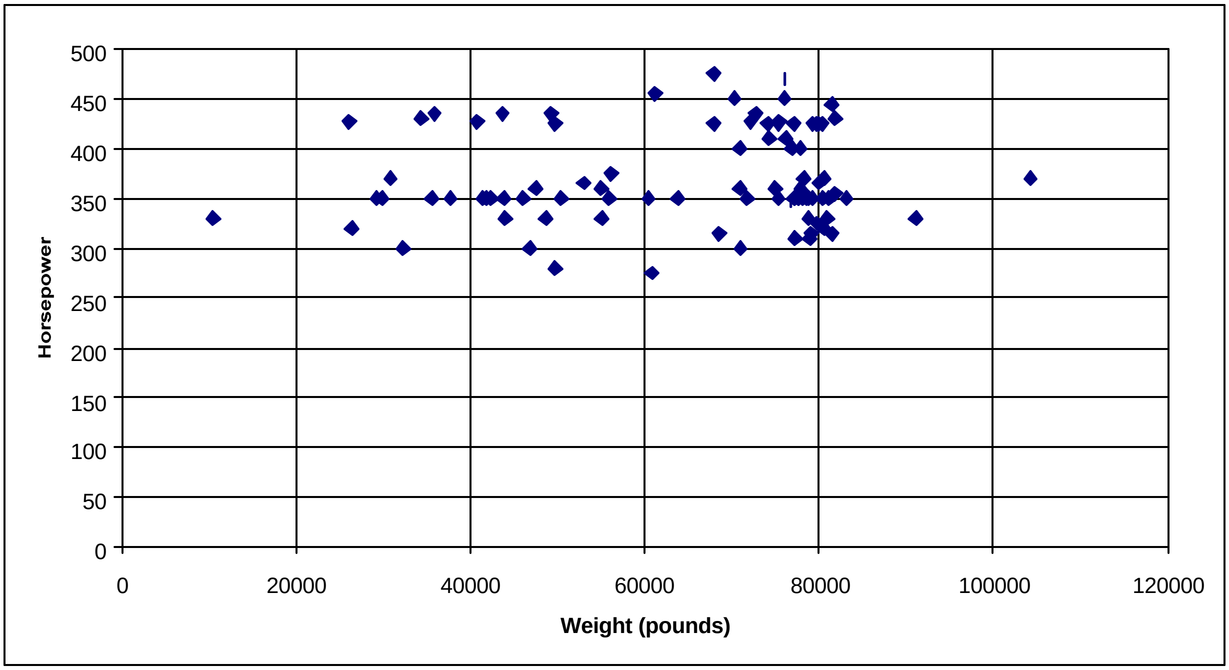


Figure 5-6: Horsepower vs. Total Weight for Class 9-13 Trucks for Preliminary Surveys

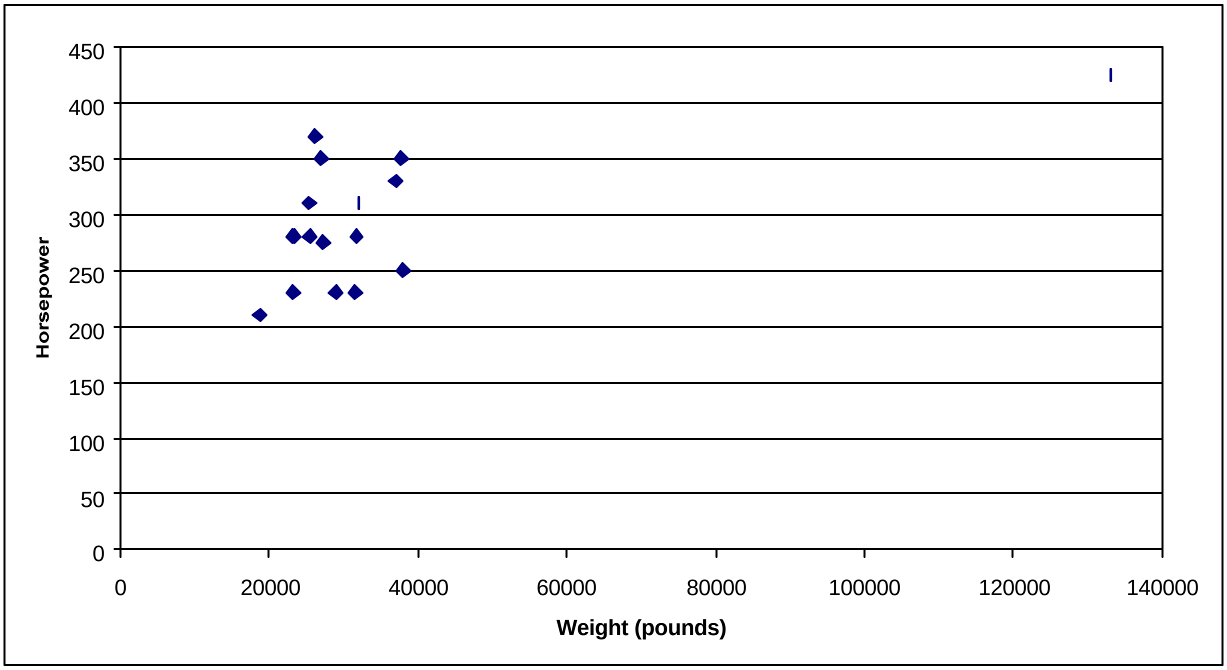


Figure 5-7: Horsepower vs. Weight for Class 8 Trucks for Preliminary Surveys

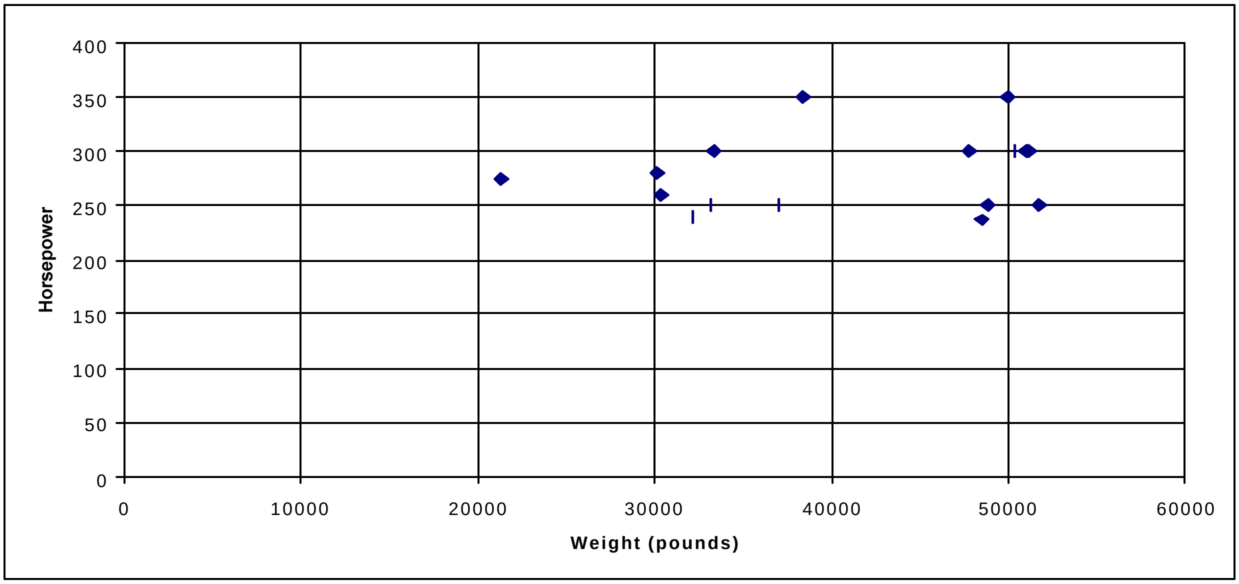


Figure 5-8: Horsepower vs. Weight for Class 6-7 Trucks for Preliminary Surveys

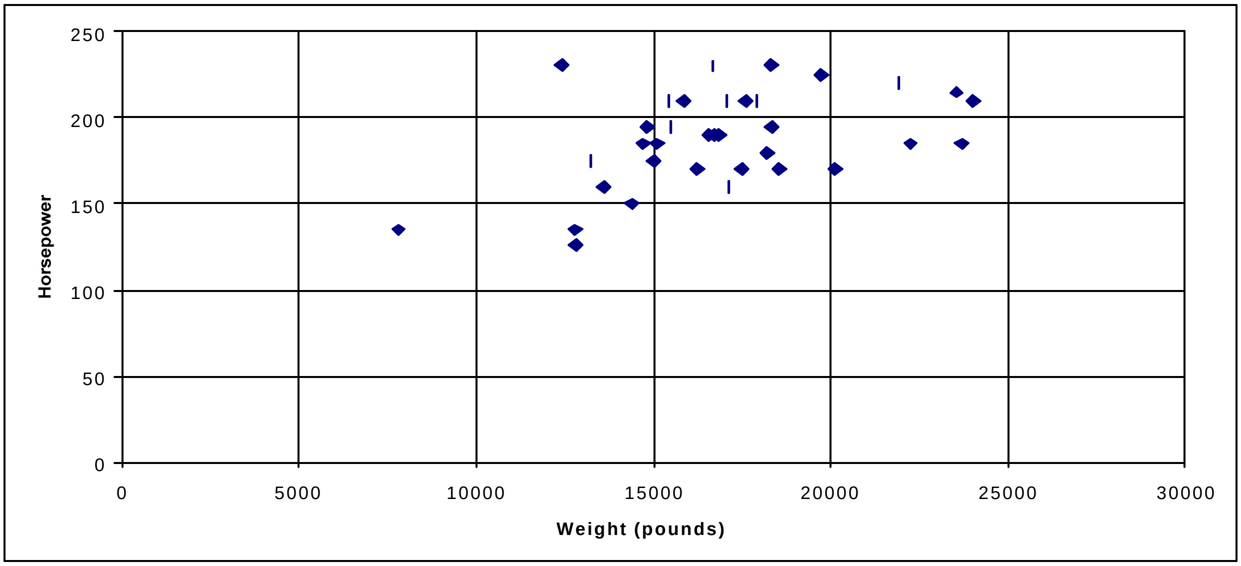


Figure 5-9: Horsepower vs. Weight for Class 5 Trucks for Preliminary Surveys

5.3 Validation of the Four Truck Classification Format

Statistical analysis was used to validate the use of the four distinct truck classes in the survey. The analysis also compared the horsepower distribution of Class 9-13 trucks taken from the overweight sample to the entire horsepower distribution for Class 9-13 trucks taken from the onroad survey. Figures 5-10 and 5-11 show the 5% significance F-values and t-statistics respectively used to determine if the variances and means of the truck classifications are different. These values are in the lower right hand corners of the tables. The letters 's' and 'd' in the upper left hand corner of the tables note whether the values are the 'same' or 'different' for a truck classification pair at a confidence level of 95%.

Figures 5-10 and 5-11 show two important results. First, the mean and the variance of the horsepower ratings of the two different Class 9-13 truck data sources can be considered to be equal. Therefore, for the purposes of this study, it is a valid assumption that the normal weight and overweight data sources can be combined into a single Class 9-13 truck classification.

Second, the results show that there is a significant difference between each of the four truck classifications defined in this study. The means are different for every paired classification except for the Class 8 trucks and the Class 6-7 trucks. However, for these two truck classifications, even though the means can not be considered statistically different, the variances are statistically different. Therefore, the two overall distributions can be considered statistically different.

These results validate the original assumption made in this survey that the truck population could be analyzed by disaggregating it into four distinct tractor-trailer configurations. The four classifications can not be combined further without losing some integrity in the independence of horsepower and weight distributions for each of the truck classifications. The classes can not be expanded without creating truck classifications lacking a significant number of vehicles for that class in real-world data. These four classifications appear to be the best structure for modeling the truck population for data collection involving both roadside surveys and portable WIM equipment. The four-truck classification system will be used in emissions modeling because they have different weight and horsepower distributions. However, there is still a need to examine these relationships at other sites where heavy-duty truck characteristics and activity levels are different to determine if these results can be applied universally to all facility types.

	Class 9-13 (svy)	Class 9-13 (ovr)	Class 8	Class 6-7	Class 5
Class 9-13 svy		s	s	d	d
Class 9-13 ovr	1.561		s	s	d
Class 8	1.258	1.963		d	d
Class 6-7	2.089	1.339	2.628		s
Class 5	3.297	2.113	4.147	1.578	

Figure 5-10: F-values and Test for Difference of Variances

	Class 9-13 (svy)	Class 9-13 (ovr)	Class 8	Class 6-7	Class 5
Class 9-13 svy		s	d	d	d
Class 9-13 ovr	-0.29		d	d	d
Class 8	5.21	5.23		s	d
Class 6-7	9.03	8.68	-0.90		d
Class 5	23.00	20.97	7.46	10.05	

Figure 5-11: T-statistic values and Test for Difference of Means

5.4 Implications of Preliminary Surveys

A number of important results were generated by the preliminary truck surveys. This research indicates that the four-truck classification format is valid for generating horsepower and weight distributions. In addition, the relationships between truck classification, truck weight, and truck horsepower for the overall truck population have been established. Additionally, the horsepower ratings of the trucks within each of the four truck classifications were found to be independent of the truck weights in those four classes for the data collected at the Douglas County weigh station. Therefore, although a horsepower-weight relationship exists for the overall truck fleet, when the fleet is disaggregated into the four classes, this disaggregation appears to be sufficient to explain the horsepower-weight relationship for all heavy-duty trucks. Additional work will be conducted to test this hypothesis at additional sites to determine if these results apply to locations with different heavy-duty truck fleet and activity levels.

The relationship between horsepower and weight is important for understanding whether empty Class 9-13 trucks tend to have lower horsepower ratings than Class 9-13 trucks traveling at full capacity. It was hypothesized that this might occur due to two factors:

1) truck companies that tend to have lighter loads might purchase vehicles that have a lower horsepower ratings based on the cheaper cost of lower rated vehicles, or

2) truck companies with very large fleets might dispatch their fleet in such a manner that the higher horsepower rated vehicles make the trips with the heavy loads while the smaller loads are carried by vehicles in the same truck classification but with a lower horsepower rating.

This independence between horsepower and weight does not negate the possibility that truck companies dispatch higher horsepower trucks for higher loads or the possibility that companies that carry lighter loads purchase trucks with smaller engines. However, the results do indicate that the relationship between truck weight and horsepower for the overall truck fleet can be successfully determined through consideration of the truck axle-trailer configuration.

CHAPTER 6

6. PORTABLE WEIGH-IN-MOTION CALIBRATION

The use of portable WIM equipment for metropolitan-level emissions modeling is a new phenomenon. The numerous sources of error for this equipment under ideal circumstances are a subject of ongoing research (Wu, 1996, ASTM, 1994; Cambridge Systematics, 1994, Dahlin, 1992, Chira-Chavala, 1986, Gardner, 1983). The state DOTs which currently collect weight data using portable WIM equipment have yet to detail the error in their results which makes incorporation of existing state DOT weight data virtually impossible for emissions modeling.

For this study, preliminary weight data were collected using portable WIMs to determine the primary sources of equipment variability. In addition, the accuracy of weight readings is also established based on preliminary data. The data collected using the portable WIMs are compared to weight data collected at the Douglas County weigh station and to data collected from the Advantage 75 weigh stations. The data from these weigh stations serve as the primary determinants of the adjustment factors for the raw portable WIM data.

6.1 Portable Weigh-In-Motion Operations

The International Road Dynamics Portable WIM Model 1070 roadside electronics unit was used to conduct weight data collection at portable sites. Onroad equipment at each site consisted of a temporary inductive loop upstream of two temporary piezoelectric sensors (Figure 6-1). All onroad equipment pieces were installed directly on top of the road surface in the traffic stream. The inductive loop was used to detect the presence of vehicles and activates the piezoelectric sensors. As the vehicle passes over the sensors, the pressure applied by an axle is translated into a voltage reading and finally into a weight estimate by the roadside electronic unit. The electronic unit also collects time-stamped data on speed, axle spacing, and vehicle length for each vehicle and stores the data in binary format. Using the office software, the binary data are downloaded onto a spreadsheet for analysis.

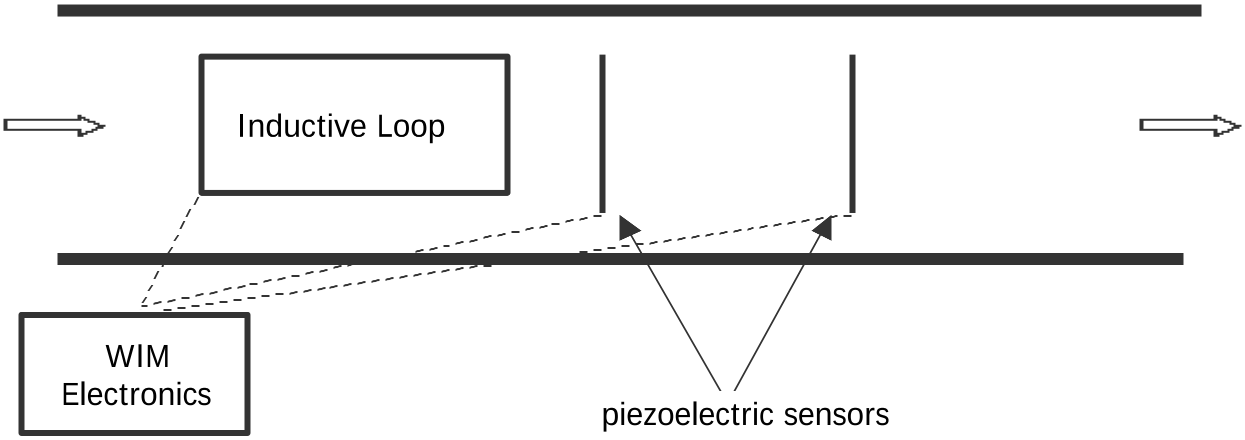


Figure 6-1: Layout of Portable WIM Installation

6.2 Portable WIM Equipment Accuracy Issues

The traditional method of calibrating weigh-in-motion sites is through the use of a single test truck at a single weight. The test truck passes over the equipment several times and the calibration factor of the equipment is adjusted until the weight reading of the equipment is within a specified range of the known weight of the test truck. This method ignores possible sources of equipment error such as error from different vehicle classifications, error across the full range of vehicle weights, and temperature sensitivity of weigh-in-motion equipment. The traditional calibration method even has questionable accuracy for vehicles with the identical weight and axle-trailer configuration as the test truck. Research suggests that the dynamics of any specific truck are very unique and can be different from other trucks even those of the same vehicle classification (Dahlin, 1992).

Alternative methods have been developed to calibrate WIM equipment, but the methods vary with the type of equipment used and the primary vehicles of concern for weight data collection (Wu, 1996; Papagiannakis et al., 1996; Dahlin, 1992; Fekpe et al., 1992). A comprehensive calibration method for portable weigh-in-motion equipment used in conjunction with temporary loops and sensors has not yet been developed.

The lack of a standardized procedure for the acceptance of WIM systems, performance standards, and calibration methods led the American Society for Testing and Materials (ASTM) to examine WIM equipment. The ASTM procedure for WIM acceptance and calibration involves using a combination of test trucks and statically-weighed, randomly-selected vehicles from the traffic stream (ASTM, 1990). Although this is an improved method, it is impractical to use in most cases due to the unavailability of static scales at most portable WIM sites.

The primary factors influencing the weight distribution of the portable WIM equipment are a calibration effect of the WIM electronics, temperature sensitivity of the onroad equipment, an internal algorithm, and random error.

6.2.1 Calibration Effect

The calibration effect of the weight distribution is a systematic phenomenon of the portable WIM equipment. The basic problem is that truck weight readings that are far from the weight of the test truck used to develop the initial calibration factor are routinely recorded as closer to the weight of the test truck than they are in reality. For example, if a site was calibrated with a 70,000 pound truck, then 35,000 pound empty trucks could be recorded as high as 45,000 to 50,000 pounds depending on site location characteristics, temperature, and other factors.

This “compression” can be easily identified from the location of the empty and full Class 9 truck peaks in the portable WIM data relative to the weigh station WIM data for Class 9 trucks. As a result of the high percentages of completely empty or full trucks in the onroad Class 9-13 truck fleet, the typical form of an accurate Class 9-13 weight distribution is constant at different locations. The shape of the curve will contain two peaks: one near the weight of empty trucks (35,000 pounds) and one near the weight of full trucks (75,000 pounds) such as that shown in Figure 6-2. This can be contrasted to the Class 9-13 weight distribution of the portable WIM data in Cobb County between 12AM and 2AM which has its peaks at 42,500 pounds and 72,500 pounds for empty and full trucks respectively (Figure 6-3). Compression of the weight distribution curve is the largest source of error in the raw readings of the portable WIMs.

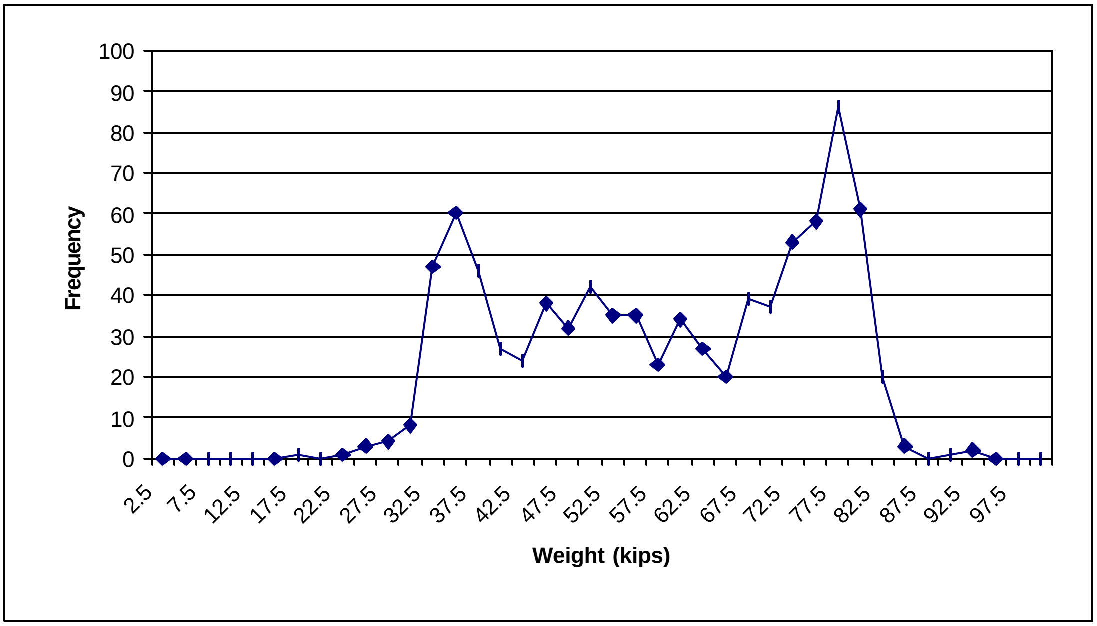


Figure 6-2: Weight Distribution of Class 9 Trucks, Monroe County Weigh Station, April 12, 1998, Noon-2PM

6.2.2 Temperature Sensitivity

Temperature sensitivity of portable WIM equipment is also a limiting factor in the accuracy of portable WIM equipment used in combination with temporary WIM sites. Figure 6-3 shows the weight distribution of Class 9 trucks for two three-hour time periods beginning at noon and midnight at the Cobb County portable WIM site. The midnight weight distribution is shifted to the right by about 10,000 to 15,000 pounds. This type of shift is standard for portable WIM data collected during night time hours relative to data collected in the daytime. The shift is the result of temperature sensitivity of the portable WIM equipment. Recall that for Class 9 trucks the weight distribution contains a curve with two peaks at identical locations (one near 35,000 pounds and one near 75,000 pounds) regardless of site location or the time period of data collection. Therefore, a horizontal shift of the entire distribution can not be accounted for by differences in shipping patterns between daytime and night time trucks.

The temperature sensitivity of the equipment results in weight readings that are significantly higher during the coldest hours of the night relative to the hottest hours of the day. The data collected at the Monroe County weigh station show that the location of the empty and full truck peaks should be identical for different times of day (Figure 6-4) further indicating the existence of temperature sensitivity of the portable WIM equipment.

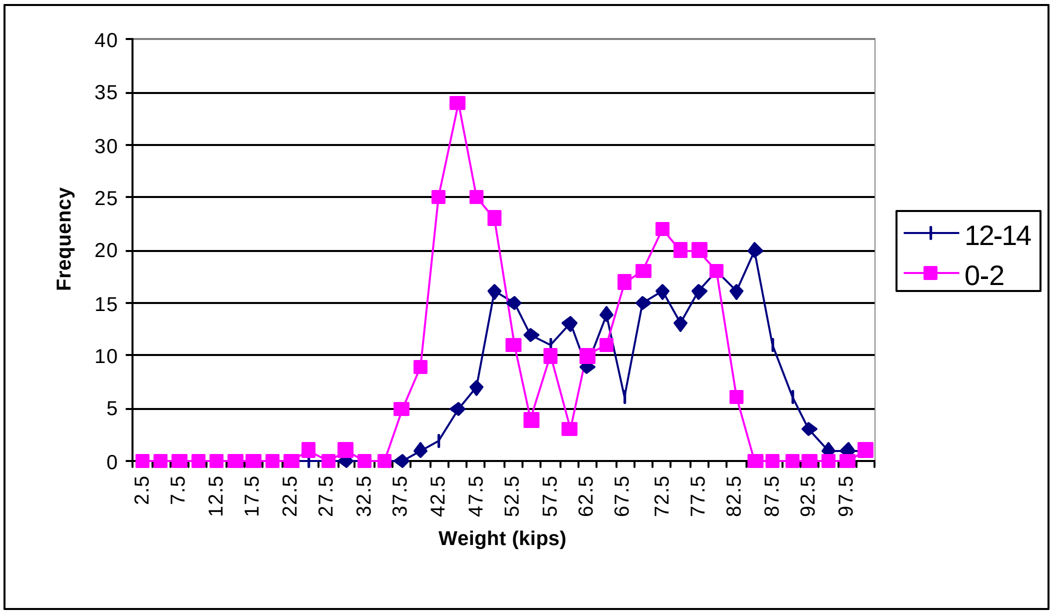


Figure 6-3: Raw Weight Distributions During Different Hourly Time Periods, I-75 Cobb County, April 12, 1997

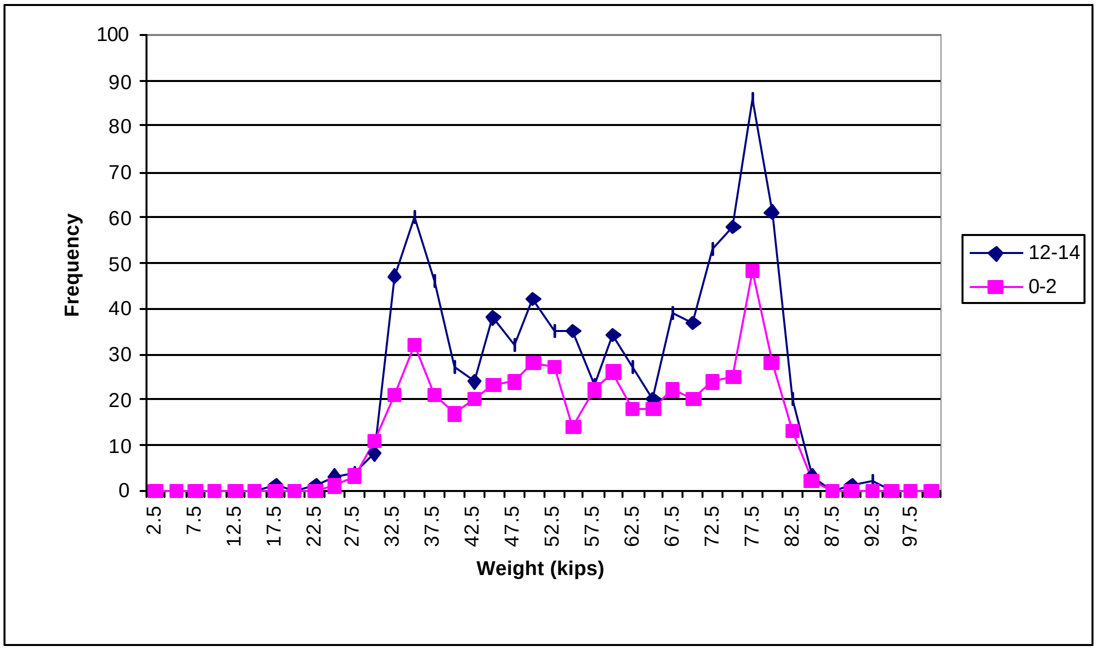


Figure 6-4: Weight Distributions During Different Hourly Periods, Monroe County Weigh Station, April 1998

6.2.3 Internal Algorithm

There is an internal algorithm in the portable WIM electronics software that adjusts the calibration factor based on the first axle weight readings of every 100 5-axle trucks. The basis for the algorithm is that despite the large variation in the gross vehicle weights of 5-axle trucks, the weight of the first axle remains within a much more narrow band. When the weight readings of the average of 100 consecutive first axles fall outside that band then the calibration factor is adjusted automatically. This algorithm is designed to buffer against the potentially large inaccuracies that are a result of the temperature sensitivity and drift of the weight readings over time. However, the presence of this algorithm creates an additional source of uncertainty in the weight readings, because it is very difficult to determine the exact times and amounts of adjustment to the calibration factor. However, this factor accounts for a maximum of 10% variability between a pair of weight readings, and between hourly data sets the variability would be negligible.

6.2.4 Random Error

There is also the random error associated with WIM readings in general. There is extensive literature on the errors involved with the most accurate WIM devices. This error is based on the random nature in which a vehicle passes over the onroad WIM equipment. Vehicles exhibit a certain amount of vertical vibration throughout the driving process. The vertical position of the vehicle as it crosses the onroad equipment determines the amount of the vehicle weight that is recorded by the WIM. The variation in the vertical position translates into variance in weight readings. A single test truck was used to calibrate the portable WIM equipment in Cobb County using the traditional calibration technique. The readings from the test truck did not vary by more than 5% for ten test runs.

6.3 Post-Processing to Increase WIM Accuracy

6.3.1 Standard Post-Processing

The standard method for dealing with equipment inaccuracy is to develop factors to account for each of the sources of inaccuracy and adjust the weight readings on an individual basis according to the derived factors. For the portable WIM equipment the errors from compression and temperature sensitivity can be estimated through a regression of the actual weight versus the raw weight readings from the portable WIM equipment.

The portable WIM equipment was installed at a location ¼ mile upstream from the Douglas County Weigh Station to compare the portable WIM equipment data to the WIM scales of the weigh station. The weigh station WIM scale has been shown to be accurate to within 2% of static scale weights. Temperature data were collected from the records of the National Weather Service. The National Weather Service records temperature readings every three hours at Hartsfield International Airport in Atlanta approximately 15 miles from the weigh station. The temperature readings for individual vehicles were estimated under the assumption of a linearly changing temperature in between the three-hour periods. For example, if the

National Weather Service recorded temperatures of 61 and 64 degrees Fahrenheit for 1PM and 4PM respectively, then the temperatures for 2PM and 3PM would be assumed to be 62 and 63 degrees respectively.

Appendix A measures the accuracy of the portable WIM equipment. Figure A-1 in Appendix A shows the raw data collected over seven different days at the weigh station comparing portable WIM readings and actual readings. As a result of the limited operating hours of the weigh station, nighttime readings could not be incorporated into the data set. Therefore, the data include only a limited range of daytime temperatures.

In general, there is a linear relationship between the raw vehicle weights and the actual vehicle weights. A linear regression was performed on the data with the actual weight as the independent variable and the portable WIM raw weight and the temperature as the dependent variables. This regression showed that both of the dependent variables have coefficients that are likely above zero. A relatively high R^2 value of 87.7% was achieved with unbiased residuals for both the temperature and predicted weights of each of the observations.

However, the residuals for the actual weights for each of the individual weight classes showed that the linear regression does not completely account for the calibration effect of the equipment described earlier. Even when applying the transformation developed through the linear regression, the lower weights for the Class 9 trucks are overweighed by the portable WIM equipment and the heavy weights are underweighed. Numerous nonlinear transformations of both the independent and dependent variables failed to generate improved regressions based on either R^2 or the shape of residual scatterplots. The inability of the traditional calibration method to account for the compression of the calibration effect is a primary factor that was considered in the selection of a non-traditional method of post-processing the raw portable WIM weight readings. The following factors also complicate the application of the traditional method to the portable WIM:

- the temperature data of the comparison data set was limited to a small range of daytime temperatures rather than the full range of day and nighttime temperatures as a result of the limited operating hours of the weigh station,
- the potential for differences between the relationship of the actual weight versus the raw portable WIM weight and the temperature at different locations due to differences in the surface or differences in installation techniques, and
- the difficulty in calibrating each site with identical techniques due to the varying availability of calibration trucks at the time of equipment installations.

6.3.2 Manual Peak-Shifting (MPS) Method of Post Processing

Manual peak-shifting (MPS) is a post-processing method whereby the raw weight readings of the portable WIM are adjusted based on known locations of the peaks of the bi-modal Class 9 and Class 6-7 truck weight distributions. Distributions of the raw portable WIM data are developed over short periods of time at a single location so that the temperature is constant and the relationship between the raw and actual weights remains the same. The peaks of the raw Class 9 and Class 6-7 truck weight distributions are identified. Adjustments are then applied to these raw weight distributions to shift the raw peaks to the correct locations. These adjustments then become the basis of proportional shifts for the entire data set for Class 9 and Class 6-7 trucks.

Additionally, Class 10-13, Class 8, and Class 5 trucks which do not exhibit weight distributions with standard peaks are post-processed based on the adjustment factors developed for Class 9 and Class 6-7 trucks. In particular, Class 10-13 trucks are shifted based on Class 9 truck adjustments. Class 8 and Class 5 trucks are shifted based on adjustments made for Class 6-7 trucks. These truck classes are matched based on similar weight ranges of the weight distribution. For example Class 10-13 trucks range from 35,000 to 80,000 pounds similar to Class 9 trucks.

Appendix A discusses the accuracy of the MPS method based on the data set collected at the Douglas County Weigh Station. The following four sections outline the MPS process for each of the four truck classes developed during the preliminary surveys.

6.3.2.1 MPS for Class 9 Trucks

Weight distributions are developed in this analysis based on 2,500 pound bins. Bins are identified based on the upper bounds of each of the intervals. Therefore, the interval containing weights between 32,500 and 35,000 pounds is referred to as the 35,000 pound interval.

The process for adjusting portable WIM readings involves the identification of two locations in the raw vehicle weight data: the empty truck peak and the full truck peak. The amount of adjustment for an individual reading depends on three factors:

1) the difference between the peak for full vehicles in the raw weight distribution and the actual peak for full vehicles,
2) the difference between the peak for empty vehicles in the raw weight distribution and the actual peak for empty vehicles, and
3) the difference between the individual raw weight reading from the peak for full and empty vehicles in the raw weight distribution.

The bin containing the empty vehicle peak of the raw weight distribution is shifted the exact amount to position this interval into the 35,000 pound interval in the final vehicle weight distribution. The bin containing the full vehicle peak of the raw weight distribution is shifted the exact amount necessary to position this interval into the 75,000 pound bin in the final vehicle weight distribution. All other raw vehicle weight readings are than adjusted linearly and proportionally based on the distance between the raw weight distribution full and empty peaks.

For example, suppose a raw weight distribution has empty and full vehicle peaks at 45,000 pounds and 70,000 pounds respectively. A vehicle that was recorded with a raw portable WIM weight reading of 45,000 pounds would be shifted exactly 10,000 pounds downward to 35,000 pounds. Similarly, a vehicle with a raw weight reading of 70,000 pounds would be shifted exactly 5,000 pounds upward to 75,000 pounds. A vehicle with a raw weight reading of 52,000 pounds is 12,000 pounds away from the raw peak for empty vehicles of 40,000 pounds and 18,000 pounds away from the raw peak for full vehicles of 70,000 pounds. The amount of the shift for the 52,000 pound vehicle is proportional to its distance from the raw peaks and the distance from the raw peaks to the actual peaks. It should be noted that this process does in some instances create raw vehicle weight readings that are less than zero. For the purposes of statistical analysis these weight readings were removed from the final weight distributions.

The existence of temperature sensitivity affects the implementation of the MPS post-processing method. To factor out the presence of any significant effect of temperature sensitivity in the raw weight readings, the MPS method is applied to the raw data in small time periods for which the temperature lacks significant variation. Three-hour time periods were determined to be small enough to assume constant temperatures for the application of the MPS method.

Use of the MPS post-processing method is based on the assumption of uniformity in the locations of the empty and full vehicle peaks for actual weight distributions throughout the Atlanta metropolitan area. Statistical analysis is not needed to verify the lack of shifting of the empty and full truck peaks between different weight distributions. It is assumed that the location of these peaks are identical at different locations and during separate time periods based on the data collected at weigh stations through the state of Georgia and weight data collected from the aforementioned studies.

Statistical analysis is used in this research to determine whether different distributions have different percentages of empty, full, and less than truckload shipments. As we shall see later in the Results chapter (Chapter 8), the MPS method does allow for the determination of significant differences between different weight distributions. Therefore, although the uniformity of the post-processing method may blur some of the distinctions between weight distributions, the effect of tractor-trailer configuration as well as temporal and spatial variability on weight distributions can be detected using the MPS method.

6.3.2.2 MPS for Class 6-7 Trucks

Similar to Class 9 trucks, Class 6-7 truck weight distributions exhibit two peaks as the result of the large fraction of completely empty or completely full trucks in the Class 6-7 truck fleet. Data from the Monroe County weigh station show that the location of the peaks are 22,500 pounds and 45,000 pounds for empty and full Class 6-7 trucks respectively. The raw Class 6-7 truck weight data collected using the portable WIMs can be adjusted using a similar MPS method as performed on raw Class 9 portable WIM truck weight data. In fact, the MPS method for Class 6-7 trucks is identical to the MPS method of Class 9 trucks with the exception that the locations of the empty and full truck peaks are different.

6.3.2.3 MPS for Class 8 Trucks

The typical Class 8 truck weight distribution resembles a normal distribution with one peak as opposed to the dual peaks exhibited in the Class 9 and Class 6-7 truck weight distributions. Therefore, a separate MPS method can not be developed for this truck classification. Instead, the post-processing for Class 8 trucks will be based on the adjustments made for Class 6-7 trucks. Class 8 trucks will be disaggregated based on the time periods of Class 6-7 trucks and the adjustment factors will be applied to each individual reading as if the reading was included in the Class 6-7 truck weight distribution. Therefore, if a 3-axle single-unit truck (Class 6) had a raw reading of 43,000 and was adjusted to 45,000 pounds, then a 3-axle double-unit truck (Class 8) with a raw reading of 43,000 pounds would also be adjusted to 45,000 pounds. The use of the Class 6-7 truck weight adjustments for Class 8 trucks is possible because the weight range of Class 6-7 trucks is similar to that of Class 8 trucks.

6.3.2.4 MPS for Class 10-13 Trucks

The weight range of Class 10-13 trucks is similar to that of the Class 9 trucks. Therefore, the adjustment factors utilized for Class 9 vehicles is used for Class 10-13 vehicles. For example, during a particular time period, if a Class 9 truck was adjusted from 58,000 pounds to 72,000 pounds, then a 58,000 pounds Class 10 truck would also be adjusted to 72,000 pounds.

6.3.2.5 MPS for Class 5 Trucks

Based on data collected at the Georgia weigh stations, the weight range of Class 5 trucks (2-axle, single-unit vehicles) is between 5,000 and 25,000 pounds. This weight range is considerably less than all other truck classes. Therefore, no adjustment factors could be developed for Class 5 vehicles. Generating weight distributions from the portable WIM equipment for this classification was not successful. Appendix A outlines the unsuccessful application of Class 6-7 adjustments to Class 5 raw weight distributions.

6.4 Development of Appropriate Temporal Periods

Post-processed Class 9 truck weight data collected along I-75 in Cobb County was used to develop appropriate temporal analysis periods for the full data set. Figure 6-5 shows the temporal fluctuations in the Class 9 weight distributions. However, the figure also shows that there is a great deal of variation between weight distributions between noon to 2PM compared to midnight to 2AM even after adjustments for temperature are applied. In particular, the daytime distribution appears to have a higher percentage of empty trucks (less than 37,500 pounds) while the nighttime distributions tend to have a higher percentage of full trucks (higher than 72,500 pounds). The MPS post-processed weight distribution for the entire data set reveals this temporal fluctuation in more detail.

Figure 6-5 also shows that the frequency of empty trucks is indeed higher at nighttime hours as opposed to daytime hours. For the weekdays there is a daytime peak period for the hours which begin from 10AM to 2PM where the amount of trucks less than 37,500 pounds is more than 25% and the percent of trucks more than 72,500 pounds is less than 20%. There is also a nighttime peak period for the hours which begin from 7PM to 11PM continuing into midnight to 7AM, where the percent of trucks less than 37,500 is less than 21% and the percent of trucks more than 72,500 pounds is around 35%. The periods beginning with the hours from 3PM to 7PM and from 8AM to 9AM are transitional periods in which the truck distribution changes from the two peak time periods.

The morning transition peak is handled by placing the hour that begins with 8AM to the nighttime peak period and shifting the hour that begins with 9AM to the daytime peak period. The late afternoon peak period (from hours 3PM to 7PM) will be considered a separate distribution. Therefore, there are three time periods for the truck weight distribution analysis:

1) daytime peak period (from the hours of 9AM to 2PM),
2) late afternoon period (from the hours of 3PM to 7PM), and
3) nighttime peak period (from the hours of 7PM to 8AM).

The Class 9 truck classification is the largest truck classification by volume on the Interstate system. Therefore, the temporal categories for the entire vehicle fleet is based on the appropriate temporal periods for this class of vehicles for the initial analysis. Following the initial analysis, there will be a check to see if any of the temporal periods can be condensed into fewer time periods for each truck classification.

	Weight Bins (000s of pounds)				
Hour Beginning	**Less than 37.5**	**37.5 to 55.5**	**55.5 to72.5**	**More than 72.5**	**Total**
Midnight	18.3%	16.8%	30.4%	34.5%	100%
1AM	17.1%	15.3%	26.8%	40.8%	100%
2AM	19.8%	13.8%	30.8%	35.8%	100%
3AM	17.9%	18.7%	24.0%	39.4%	100%
4AM	17.8%	15.9%	31.4%	34.8%	100%
5AM	16.2%	15.1%	27.0%	41.7%	100%
6AM	19.1%	15.7%	23.3%	41.9%	100%
7AM	18.5%	14.6%	25.4%	41.5%	100%
8AM	22.8%	16.1%	24.4%	36.8%	100%
9AM	20.3%	26.4%	18.3%	35.1%	100%
10AM	27.6%	28.4%	16.7%	27.3%	100%
11AM	28.6%	23.4%	19.3%	28.6%	100%
12 Noon	33.7%	22.9%	19.8%	23.5%	100%
1PM	29.0%	25.3%	18.0%	27.7%	100%
2PM	27.2%	25.7%	18.3%	28.7%	100%
3PM	24.9%	23.4%	27.0%	24.7%	100%
4PM	23.7%	22.1%	26.8%	27.4%	100%
5PM	22.7%	23.0%	20.3%	34.0%	100%
6PM	26.7%	23.8%	19.0%	30.5%	100%
7PM	22.9%	18.3%	24.9%	33.9%	100%
8PM	20.5%	13.3%	27.7%	38.5%	100%
9PM	17.4%	19.7%	24.9%	38.0%	100%
10PM	18.3%	17.6%	28.9%	35.1%	100%
11PM	19.6%	16.9%	26.7%	36.8%	100%

Figure 6-5: Percentage of Trucks in Selected Weight Bins, I-75 Cobb County, February 1997

6.5 Implications for Overall Truck Weight Data Collection

The truck weight results presented in this chapter have implications for the sampling plan of the truck weight data collection. The traditional method of calibrating equipment was found to be unfeasible for the portable WIM equipment as a result of the high number of error sources at a typical site, variability in error between sites, and the lack of access to static weight scales during an adequate temperature range. The MPS post-processing method of raw portable WIM data was found to provide unbiased and reasonably accurate weight readings for four of the five truck classifications. The amount of error which exists in the post-processed portable WIM data are small relative to the total weights of the vehicles and statistically tolerable based on the large number of heavy-duty vehicles included in each of the four main truck classes (see Appendix A).

The overall truck model will focus on examining the temporal relationship between different truck classes and weight distributions. The temporal categories were developed using the Class 9 portable WIM data collected at the I-75 Cobb County location. The full data set will be checked to determine the feasibility of combining temporal data categories into fewer data sets for the other vehicle classifications during all time periods.

CHAPTER VII

7. SPECIFICATION OF MODELS

The statistical analysis on the preliminary data from the Douglas County weigh station surveys (Chapter 5) and the portable WIM calibration process (Chapter 6) indicate that a 4-class heavy-duty vehicle classification would be appropriate for gross vehicle weight and horsepower model development. The crosstab analyses of Chapter 5 suggest that there is no relationship between gross vehicle weight and horsepower for each of these four vehicle classes. Based on these results separate models will be developed to categorize the distributions of gross vehicle weight and horsepower for each classification on the Interstates in the Atlanta metropolitan area.

The use of the portable WIMs for collection of weight data allows for the inclusion of specific time-of-day and day-of-week factors to the development of the weight models. Therefore, the gross vehicle weight models will focus on temporal fluctuations in weight distributions. Data collection on horsepower distributions will be based on truck surveys and engine manufacturers' data which precludes the inclusion of temporal variables but allows for the consideration of many variables such as model year, truck company type, and origin-destination characteristics. The horsepower models will measure the effect of each of these variables with site selection based on maximizing the geographic coverage across the Atlanta metropolitan area.

7.1 Statistical Comparison of Two Distributions

A significant amount of the statistical work performed in this research involves the detection of similarities and differences between both gross vehicle weight and horsepower distributions based on variables such as vehicle classification, data collection location, and temporal factors. As described in Chapter 5, crosstab analysis provides a convenient method of comparing two distributions.

7.2 Heavy-Duty Vehicle Weight Distribution Model

7.2.1 Response Variable

The response variable in the prediction process is the frequency of trucks in weight bins. Weight bins are established separately for each vehicle classification based on the total weight range and the quantity of data collected. Statistical analysis will proceed initially with bin sizes of 5,000 pounds. If insufficient data is collected for a particular weight class based on 5,000 pound bin sizes, then the bins will be aggregated into empty, partially loaded, and full weight bins.

7.2.2 Control Variables

The primary control variable for the weight model is the location of the portable WIM equipment. Data collection locations were chosen to represent the full range of spatial variability throughout the interstate network. The high volumes of trucks at each interstate location provided statistically significant numbers of each vehicle classification to allow for comparisons between several distributions.

7.2.2.1 Spatial Factors

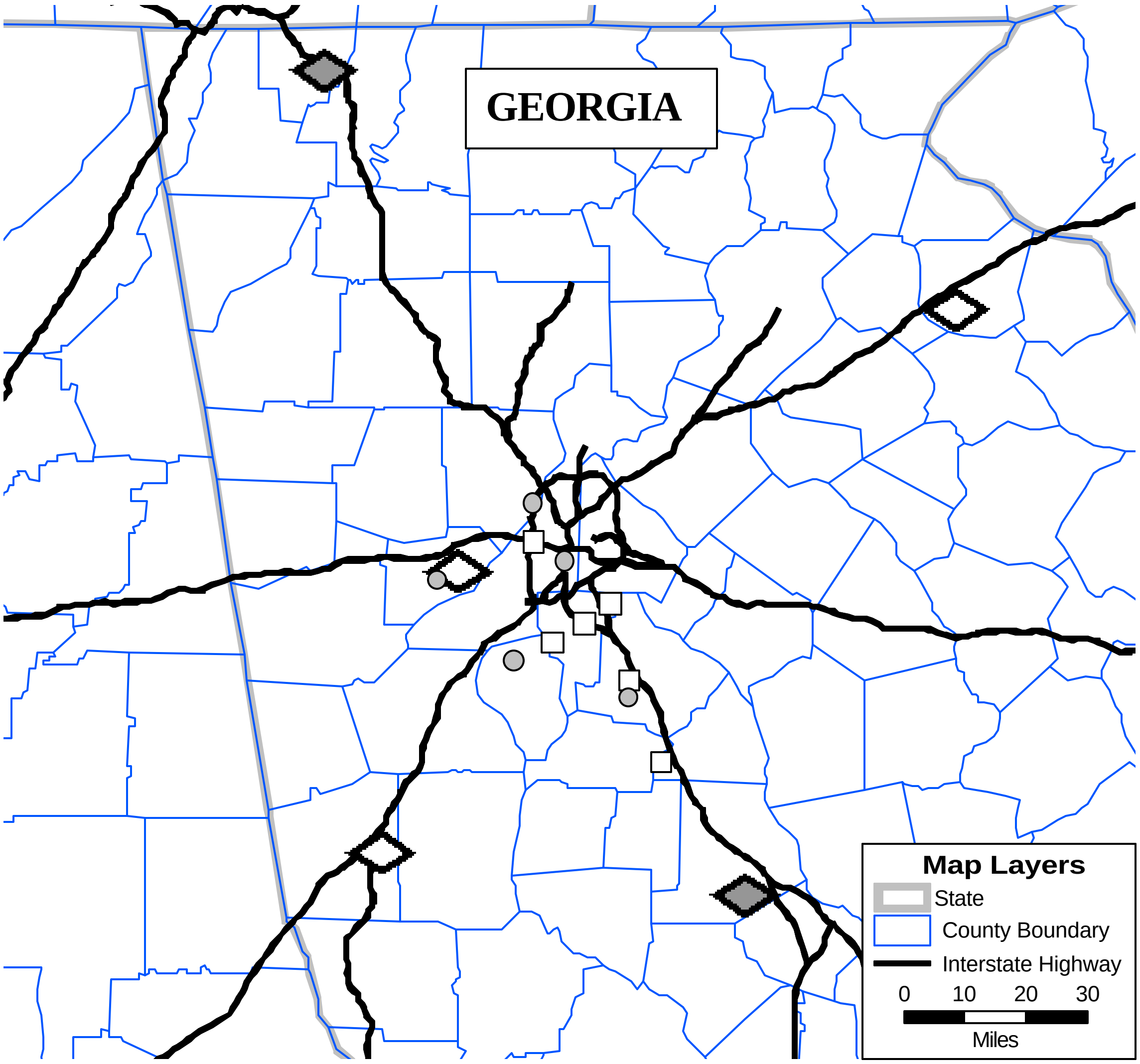
WIM data from the Advantage I-75 project show a significant difference between weight distributions at different locations for Class 8 (5-axle, 1-trailer) vehicles. These differences are likely due to spatial differences in land use characteristics. However, all of the Advantage I-75 locations are on rural Interstate locations outside of the Atlanta metropolitan area. Therefore, these results can not applied directly into to the Interstate system of Atlanta. Moreover, existing although limited research indicates that for metropolitan areas, there is not significant differentiation between weight distributions between different locations (Wegmann, 1995; Dahlin, 1992; Wu, 1996). Spatial variation in weight distribution data in the Atlanta metropolitan area would necessitate the development of a complex GVW model which would attempt to correlate differences in gross vehicle weight distributions to commodity-specific movements and land use characteristics. Through validating the lack of statistically significant spatial variance in the weight distribution data would support the focus of this research on temporal variance in weight distributions.

Spatial variability in weight distributions can also take the form of directionally unbalanced weight distributions on the Interstate system. For example, during a particular time of day the weight distributions on an Interstate can vary based on the difference between the weight distribution of inbound and outbound traffic. For major manufacturing areas such as Atlanta, the potential for high outbound traffic weights relative to inbound weights must be examined as part of the test to verify independence of weight distributions from spatial characteristics. Therefore, the data collection locations include spatial and directional coverage of the Interstate system in Atlanta as shown in Figure 7-1.

The geometric configuration of the Interstates relative to the 13-county Atlanta metropolitan study area show three spatially different categories of the Interstate system: 1) the perimeter freeway (I-285), 2) the Interstates inside the perimeter, and 3) the Interstates outside the perimeter or Interstate “legs”.

The truck traffic on the perimeter freeway and on the Interstate legs is different from the traffic on the Interstates inside the perimeter. Truck traffic inside the perimeter is prohibited for vehicles without an origin or destination inside the perimeter. In addition, the road geometry of the Interstates in the metropolitan area creates little incentive for truck trips through Atlanta to violate this rule, except for truck trips travelling along Interstate 20 which has the lowest volume of truck traffic of all the Interstates. Therefore, the truck traffic inside the perimeter has a high volume of internal truck trips while the truck traffic on the perimeter freeway and the Interstate legs has a higher percentage of external truck trips. Based on the differences in truck trips on the different interstates, site selection of the portable WIM locations will include at least one location inside the perimeter freeway for comparison to the overall truck weight distributions.

Truck weight distributions are more likely to vary on different Interstate “legs” than on different locations of the perimeter freeway. As mentioned earlier, weight distributions in rural areas of Georgia exhibited significant differences based on location. These differences are likely due to the onroad truck fleet being dominated by a particular industry class or a major land use activity. The Interstate “legs” are the most likely location of the rural weight variability influencing weight distributions in the Atlanta metropolitan area, because the “legs” are the closest Interstate locations to the rural areas. Traffic on the perimeter freeway has a lower likelihood of variability because it includes traffic from several different rural areas and a higher percentage of internal trips. Both of these factors lower the ability of a single industry or land use type from dominating the truck traffic on the perimeter freeway. The portable WIM data locations will focus on the Interstate legs in order to maximize the possibility of observing differences given the limited testing resources (see Figure 7-1).



◆ Advantage I-75 Weigh Stations (weight and survey data collected)

◇ Standard Weigh Stations (weight and survey data collected)

□ Truckstop Survey Locations (survey data only)

● Portable WIM Sites (weight data only)

Figure 7-1: Map of WIM Sites, Standard Weigh Stations, Advantage I-75 Locations, and Truckstop Survey Locations in North Georgia

7.2.2.2 Directional Traffic

As an industrial center, Atlanta generates a large fraction of a particular type of truck activity. In addition, as a metropolitan area, there are a number of goods such as food stuffs which are produced outside of Atlanta and shipped by truck inside the metropolitan area. These two forces can potentially combine to create differences in weight distributions between inbound and outbound traffic. During informal truck company interviews of three regional for-hire truck carriers located in the Atlanta metropolitan area, one company mentioned the prevalence of inbound traffic in the early morning, with local pickup and delivery continuing throughout the day, and outbound traffic in the late afternoon and evening.

Therefore, the data collection locations must also allow for the verification that this is fact not a significant factor in the weight distributions for the Atlanta metropolitan region. This requires that the data collection locations on the Interstate legs include both inbound and outbound sites.

7.2.3 Operational Variables

Operational variables include those variables that are not directly controlled for in the data collection site location. However, these factors will be checked against the weight distributions to determine if there is a relationship between the operational variable and the weight distribution. The high number of trucks sampled at each data collection location allows for vehicle classification, time of day factors, and day of week factors to be analyzed as operational variables rather than specifically controlled in the sampling plan.

7.2.3.1 Vehicle Classification

As shown in the preliminary results (Chapter 6), the vehicle classification was found to be a significant factor in the determination of gross vehicle weight distributions. This will be the primary operational variable. Distributions will be developed for the four vehicle classes established earlier with additional analysis performed on the largest of the vehicle classifications to determine if additional stratification of this class would better describe the data.

7.2.3.2 Time of Day Factors

Temporal factors are an important factor to consider for truck activity modeling. Truck count data consistently shows the relevance of time-of-day to vehicle count data (FHWA, 1999). Existing truck survey data also show that a relationship exists between both the operating hours of commercial vehicles and between the pickup and delivery schedule of a vehicle. For example, midday truck activity includes a significant amount of local pickup and deliveries in a metropolitan area. This can be contrasted with the activity of late night trucks that include a larger percentage of larger and fully loaded vehicles. The portable WIM calibration study in Chapter 6 established three time of day categories for weight distribution modeling: 1) 9AM – 3PM, 2) 3PM – 7PM, and 3) 7PM – 9AM. These time periods will be used throughout the analysis for each vehicle classification and during each day-of-week period.

7.2.3.3 Day of Week Factors

Each day of the week will be analyzed separately to determine the existence of differences between each of the primary vehicle classifications. Truck weight data at the Advantage I-75 weight stations has shown significant truck weight distribution variation on different days of the week. Additionally, truck count data on the Interstates in the Atlanta metropolitan area reveal significant differences between truck volumes during the week and on the weekend indicating the possibility of differing truck activity on different days for the metropolitan area as well (Chapter 5). However, for days of week in which distributions are found to be different, specific time of day categories will be developed for each day. Special consideration will be given to the weekday, midday periods because they are the most relevant for emissions modeling.

7.2.4 Nuisance Factors

Nuisance factors are variables which are not controlled and not of primary interest for this research. These factors can not be set to a constant level or explicitly varied for systematic experimental units. However, if these factors can be altered, then blocking or randomization is generally considered to be an appropriate sampling framework for the inclusion of these variables.

7.2.4.1 Weather

Inclement weather may delay or re-route certain types of goods movement trips more than others. In turn these shifts can potentially affect the gross vehicle weight distributions. Some drivers could decide to use non-Interstate roads during weather conditions that create bad driving conditions. Due to the continuous and unpredictable variation in weather combined with the continuous nature of the portable weigh-in-motion equipment, weather will not be explicitly considered in the analysis.

7.2.4.2 Seasonal Factors

Seasonal factors were not explicitly considered in the weight distribution model development. At the Advantage I-75 Monroe County weigh station, seasonal data were shown not to be as significant as other temporal factors such as day of week and time of day.

7.2.4.3 Lane of Traffic

All of the portable WIM data were collected on the outside lane of the Interstates due to equipment installation restraints. Therefore, one of the conditions for site selection included a significant percentage of truck traffic in the far right lane. Nevertheless, the lane of traffic can affect gross vehicle weight distributions. The outside lane of traffic is more likely to carry local traffic than the other lanes. This is particularly true for trucks that have entered the Interstate at the last entrance upstream of the WIM site and for trucks that are exiting at the next exit downstream of the WIM site. Thus, data collected from portable WIMs may be more reflective of the local land use than the actual vehicle fleet at that location.

To test the potential effect of lane of traffic on the development of weight distributions, the data from the portable WIM site collected just upstream of the Douglas County weigh station will be compared to the data collected at the other locations. At the Douglas County weigh station, all vehicles were forced to enter into the far right lane as they prepared to enter the weigh station. Therefore, heavy-duty vehicle data from all lanes of traffic were collected at this site as opposed to the single lane of traffic collected at the other portable WIM sites.

7.3 Final Truck Horsepower Model Specification

7.3.1 Response Variable

Frequency of engine horsepower in 50 unit bins will be the response variable in the prediction process for horsepower modeling. The final horsepower bins are subclasses of the three horsepower ranges identified by truck dealers during interviews: 1) low horsepower – less than 400, 2) mid-range horsepower – between 400 and 500, and 3) high horsepower – 500 or more.

7.3.2 Control Variables

The control variable used for the horsepower model is survey location. There are three types of survey locations for this study: weigh stations inside the metropolitan area, weigh stations outside the metropolitan area, and truckstops. Collecting data at all three locations will enable the comparison of engine horsepower for different facilities. To the greatest extent possible, locations will be selected that ensure geographic coverage of the entire metropolitan location. However, site selection is severely restricted by the location of weigh stations and truckstops.

7.3.3 Operational Variables

7.3.3.1 Truck Company Type

Truck companies are categorized into two types: 1) for-hire carriers which are trucking companies that carry other company's goods and 2) private companies which exclusively carry the goods of their company. The majority of the truck surveys conducted at weigh stations contain truck company type as a data collection item. This will enable the comparison between the two company types for potentially differentiating between horsepower distributions. Theoretically, it is possible for horsepower distributions for for-hire carriers to be on average higher than that of private companies, because these companies are more likely to purchase vehicles with optimal performance capabilities in several different environments which would require highly rated horsepower engines. Trucks of private companies are more likely to be used in specific regions or routes that could likely be accomplished by lower rated horsepower engines.

7.3.3.2. Model Year

The model year is a variable that is potentially related to the horsepower of the truck. This is possible due to technological advances that allow for the increase in engine horsepower without compromising the fuel efficiency of the engine or significantly increasing the price of the vehicle. Truck drivers prefer higher horsepower engines because they provide sufficient power for handling steep grades and heavy loads. As the technology improves over time the horsepower distributions of later model year trucks likely increases. It should be noted that there is also the possibility of a correlation between model year and truck company type. For-hire carriers are likely to have newer trucks than private companies based on higher annual miles traveled for for-hire vehicles.

7.3.3.3 Origin-Destination Type

Origin-destination combination can also affect horsepower distributions if there is a correlation between horsepower and distance traveled. Truck dispatchers may attempt to match engine horsepower to loads to minimize fuel consumption. Data collected at weigh stations will specify the cities of origins and destinations if they are inside the state of Georgia, and the state of origin and/or destination for trip ends located outside the state. Based on the borders of the 13-county study area of this research, trips will be divided into four categories: 1) internal-internal trips, 2) internal-external trips, 3) external-internal trips, and 4) external-external trips.

7.3.3.4 Body Type

Although the body types of most vehicles within each vehicle classifications is generally uniform, for vehicles with five or more axles there are occasional differences which potentially can be related to horsepower differences between various body types. For this larger classification body types can be categorized as dry containers, open containers, flatbeds, tankers, and car carriers. Each of these body types has advantages and disadvantages for shipping different commodity types. Therefore, they may operate in different environments and have different horsepower distributions.

7.3.4 Factors “Held Constant”

7.3.4.1 Vehicle Classification

The only vehicle classification included in the final horsepower surveys is Class 9-13 vehicles (5 or more axles with 1 or more trailers). At the majority of data collection locations, Class 9-13 vehicles were over 90% of the heavy-duty vehicles in the traffic stream. Representative sampling of the smaller vehicle classifications was not possible.

7.3.4.2 Temporal Factors

All horsepower surveys were conducted during the midday hours between Monday and Friday. This time period was selected to minimize the data collection effort and to reflect the temporal factors of primary importance for emissions estimations. However, temporal differences may exist between weekday and weekend horsepower data or midday and off-peak horsepower data due to the differing origin-destination combinations and the increased necessity of operating efficiency during off-peak truck travel hours.

7.3.4.3 Weather

Unlike the weight data which were collected during unpredictable and continuous weather conditions, the truck surveys can only be conducted during daylight, calm weather conditions in which a sufficiently high volume of trucks would be willing to participate in the surveys in an environment conducive to information exchange. It is unlikely that weather conditions would affect the dispatch of trucks based on horsepower considerations within particular vehicle classes.

7.3.5 Nuisance Factors

7.3.5.1 Driver Participation

The primary nuisance factors are related to truck driver's willingness and ability to participate in the truck surveys. It is possible that truck drivers of older vehicles are less likely to disclose truck information then truck drivers of newer vehicles due sub-standard vehicle performance conditions. These sub-standard truck conditions are also possibly correlated to lower horsepower rated engines. Driver participation in the truck surveys was over 95%. Therefore, the affect of this nuisance factor is minimal.

7.3.5.2 Availability of Truck Information

There are two important aspects in the availability of truck information: accessing truck driver information during surveys and decoding survey data into final relevant data. First, due to missing or improperly placed VINs, a small fraction of the vehicles surveyed did not include this data item. The VIN is used in the surveys to extract the model year data and also as one of the means of determining the horsepower of the vehicle. The second means of determining the horsepower of the vehicle is driver identification. Drivers who are unable to identify the horsepower of the truck are more likely to be part of large truck companies rather than truck owner-operators. Therefore, using driver identification as a means of determining horsepower may over-sample small truck companies.

Specific horsepower data can not always be generated from successfully surveyed VINs. This can occur for one of three reasons:

1) some truck manufacturer records contain only horsepower range and not a specific value,
2) some truck manufacturer records are incomplete at time of purchase, and
3) some older vehicles predate the existence of horsepower matching databases and VINs could not be decoded.

The inability to include the horsepower data of older vehicles is a potential problem in the creation of truck horsepower distributions, especially given the possibility of a relationship between model year and horsepower ratings. The preliminary truck survey in Chapter 5 had a success rate of about 70% for Class 9-13 vehicles. Many of the unsuccessful survey items were directly attributable to a particular truck company that had poor records.

CHAPTER VIII

8. PRESENTATION OF DATA AND MODELS

8.1 Horsepower Data and Model

Horsepower data were collected to determine the relationship between gross vehicle weight and horsepower and to develop models to estimate the horsepower distribution for the heavy-duty vehicle fleet. The data collected also enabled examination of horsepower distributions with trip type, model year, and truck company type. The numerous contingency tables and chi-square valuations performed for the analyses are shown in detail in Appendix B.

Horsepower surveys were conducted at four weigh stations including repeated surveys at the Douglas County weigh station. Truck surveys at weigh stations included both origin-destination information for the majority of trucks and VIN data which could be translated into specific vehicle characteristics information. The seven surveys conducted at truckstops included only gross vehicle weight from the scales and horsepower data based on driver identification. In total, over 400 trucks were included in the surveys. Figure 8-1 shows summaries of the data collected at each survey location. The horsepower distribution for the entire data set is shown in Figure 8-2 using 25 unit bins.

Data Collection Location	Metropolitan Location	Number Surveys	Number Sampled	O-D data included	VIN data included
Douglas County Weigh Station	I-20, 15 miles W of downtown Atlanta	7	162	Y	Y
Franklin County Weigh Station	I-85 50 miles NE of downtown Atlanta	1	45	Y	Y
Monroe County Weigh Station	I-75, 45 miles SE of downtown Atlanta	1	46	Y	Y
Troup County Weigh Station	I-85, 60 miles SW of downtown Atlanta	1	48	Y	Y
Petro #22 Truckstop	I-285 Exit 8 (Bankhead Hwy)	2	54	N	N
Pilot #331 Truckstop	I-285 Exit 37 (Bouldercrest Rd.)	1	18	N	N
Travel Centers of America Truckstop	I-285 Exit 39 (Moreland Ave.),	1	14	N	N
10-4 Truck Stop	I-75 Exit 59 (Forest Pkwy),	1	20	N	N
Liberty Center Texaco Truckstop	I-75 Exit 69 (Jackson, GA)	1	15	N	N
Pit Stop Truckstop		1	17	N	N
TOTAL		18	439	-	-

Figure 8-1, Description of Truck Survey Locations and Data Collected

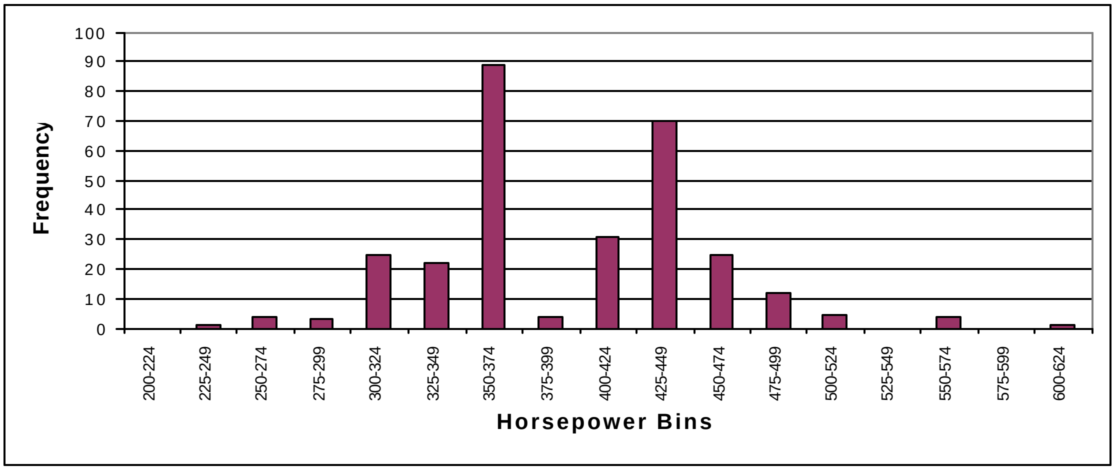


Figure 8-2, Horsepower Distribution for All Class 9-13 Truck Data

8.1.1 Relationship Between GVW and HP

Crosstab analysis (as described in Chapter 5) was performed to determine if there was a statistically significant relationship between GVW and HP for the entire data set. Figure 8-3 shows a scatterplot of the HP and the GVW for the combined data. The contingency table for the crosstab analysis comparing GVW bins and HP bins is shown in Figure B-1 in Appendix B. 50 unit horsepower bins are used for the analysis based on interviews with truck dealers as described in Chapter 7.

The χ^2 value for the crosstab analysis (14.4) is lower than the 5% significance value of the χ^2 distribution for 12 degrees of freedom (15.5). The results show that there is no statistically significant difference between the horsepower and weight for the entire data set. In addition, a regression of the full data set resulted in a coefficient for the slope of the line of 0.352 and a 95% level confidence interval for the coefficient of -0.015 to 0.732. Because the interval of the coefficient includes the value zero, the regression indicates that there is no relationship between gross vehicle weight and horsepower.

The combined crosstab and regression results are strong indications that weight and horsepower can be considered as independent variables for Class 9-13 trucks. Therefore, it does not appear that trucking companies match engine horsepower to the weights of loads for Class 9-13 trucks. This result confirms the results from the preliminary truck surveys (Chapter 5) which also showed no statistically significant relationship between GVW and HP. These results from both the preliminary and final analysis indicate that the development of separate models for GVW and HP is justified.

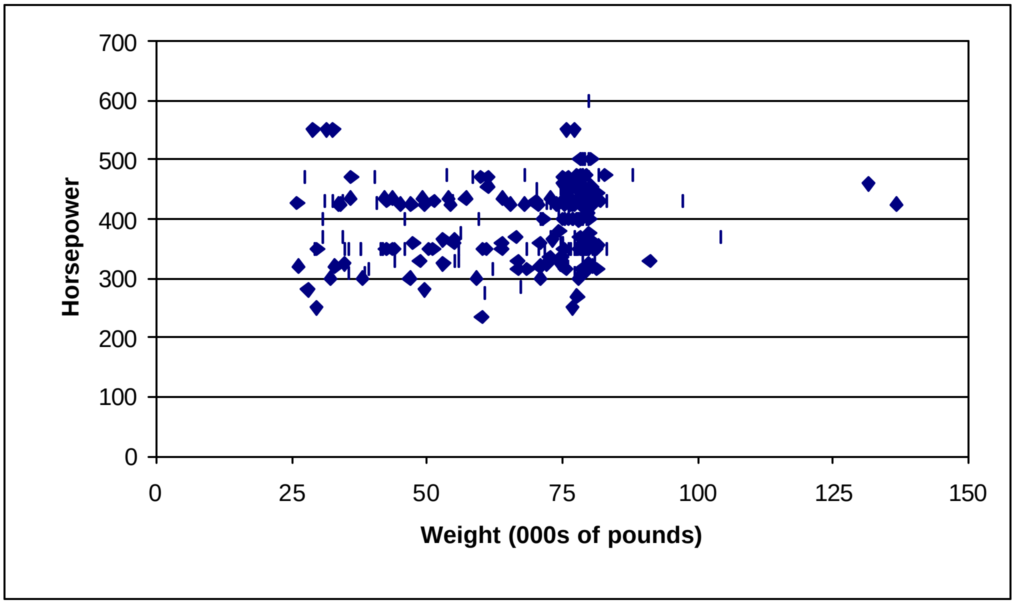


Figure 8-3, Scatterplot of Horsepower vs. GVW for all Class 9-13 Trucks

8.1.2 Horsepower Distributions at Different Locations

Crosstab analyses were performed comparing the horsepower distributions at different locations to check for spatial variability in horsepower distributions throughout the Atlanta metropolitan area. There are three facility types included in the analysis: truckstops, weigh stations inside the study area, and weigh stations outside the study area.

8.1.2.1 Horsepower Distributions at Different Truckstops

A total of 137 trucks were sampled using truckstop surveys. Figure B-2 shows the contingency table for engine horsepower and truckstop locations. The bins less than 350 HP and 350-399 HP were combined due to the small number of observations for horsepower less than 350. The χ^2 value for the crosstab analysis (17.8) is lower than the 5% significance value of the χ^2 distribution for 12 degrees of freedom (21.0). Therefore, there is no statistically significant correlation between the horsepower collected at different truckstop locations. The horsepower distributions at the truckstops can be combined into a single data set (noted as combined truckstops) for comparison with horsepower at other locations.

8.1.2.2 Horsepower Distributions at Weigh Stations and Combined Truckstops

Two crosstab analyses were performed on a total of 453 trucks from all survey locations to determine the relationship between HP distributions at different locations. The crosstab analysis that included the entire Douglas County survey data showed differences between HP distributions by location based on a 29.5 χ^2-value for the crosstab analysis being higher than 21.0, the 5% significance value of the χ^2 distribution for 12 degrees of freedom (Figure B-3).

However, for a crosstab analysis comparing only Douglas County weigh station data collected in 1999, the χ^2 value for the crosstab analysis falls to 18.4 which is lower than 21.0 (Figure B-4). All of the truckstop data were collected during 1998, while the initial Douglas County data were collected in 1996 and early 1997. Therefore, for data collected in 1998 and 1999, there is no statistically significant relationship between HP distribution and locations. These results indicate that on the Interstates, the engine horsepower distributions are the same throughout the Atlanta metropolitan region.

The difference in HP distribution found for the crosstab analysis that included the entire Douglas County data set was likely due to the inclusion of older model year trucks in the 1996 and 1997 surveys. These older surveys had a higher percentage of older model year trucks relative to the 1998 and 1999 surveys. Therefore, the horsepower distributions were likely statistically different based on time of survey rather than survey location. The relationship between model year and horsepower distribution is examined in the following section.

8.1.3 Horsepower Distributions by Model Year

Figure 8-4 shows the descriptive statistics for different model year categories for the entire survey data set. Not surprisingly, the mean horsepower is generally higher for newer trucks. There also appear to be three model year categories based on the data in Figure 8-4: pre-1996, 1996, and 1997-1999. Pre-1996 model year trucks have mean engine horsepower around 375. Model year 1996 trucks have a mean horsepower of approximately 400. 1997-1999 model year trucks have mean engine horsepower much larger than 400.

Model Year	1982	1983	1984	1985	1986	1987	1988	1989	1990
Mean	350.0	350.0	350.0	416.7	380.0	358.6	367.5	373.6	369.2
Lower CI	n/a	n/a	306.1	104.1	346.0	304.4	339.5	333.8	339.6
Upper CI	n/a	n/a	393.9	729.2	414.0	412.7	395.4	413.3	398.9
Standard Deviation	n/a	n/a	35.4	125.8	27.4	58.6	46.2	43.0	49.1
Count	1	1	5	3	5	7	13	7	13
Confidence Level(95.0%)	n/a	n/a	43.9	312.6	34.0	54.2	27.9	39.8	29.7

Figure 8-4(a), Statistical Description for Model Years 1982-1990

Model Year	1991	1992	1993	1994	1995	1996	1997	1998	1999
Mean	362.9	374.7	379.5	373.7	372.9	398.6	431.0	416.0	430.6
Lower CI	335.8	350.9	359.5	357.7	352.3	377.8	412.3	393.7	378.7
Upper CI	390.0	398.4	399.5	389.7	393.5	419.3	449.7	438.2	482.6
Standard Deviation	46.9	44.6	50.6	50.8	58.1	61.3	56.1	57.4	62.1
Count	14	16	27	41	33	36	37	28	8
Confidence Level(95.0%)	27.1	23.7	20.0	16.0	20.6	20.7	18.7	22.2	51.9

Figure 8-4(b) cont'd, Statistical Description for Model Years 1991-1999

Both the 1996 and the post-1996 horsepower distributions are statistically different from the pre-1996 horsepower distributions based on intervals of the mean at a 90% confidence level as shown in Figure 8-5. However, the 1996 and 1997-1999 distributions have confidence intervals for their respective means which overlap and therefore can not be considered different distributions. Therefore, there are two statistically significant model year categories based on the survey data: 1) pre-1996 and 2) 1996-1999. These two model year categories will be the basis of the horsepower model. Specifically, there will be two horsepower distributions, one distribution for pre-1996 model years trucks and one distribution for 1996 and newer model year trucks as shown numerically in Figure 8-6 and graphically in Figure 8-7.

It should be noted that these two figures are broken into 25 unit bins from 200 to 600 engine horsepower to provide detail. The statistical analyses were performed on 50 unit bins from 300 to 500 engine horsepower.

Model Year Category	pre-1996	1996	1997-1999
Mean	372.3	398.6	425.2
Standard Deviation	50.7	61.3	56.9
Lower CI	366.2	381.3	414.1
Upper CI	378.5	415.8	436.3
Count	186	36	73
Confidence Interval (90%)	6.2	17.3	11.1

Figure 8-5, Statistical Description for Model Year Categories (90% CI)

	Actual Counts		Probabilities	
HP Bins	pre-1996	1996-1999	pre-1996	1996-1999
200-224	0	0	0.000	0.000
225-249	1	0	0.005	0.000
250-274	4	0	0.022	0.000
275-299	2	1	0.011	0.009
300-324	19	6	0.102	0.055
325-349	16	6	0.086	0.055
350-374	67	22	0.360	0.202
375-399	2	2	0.011	0.018
400-424	23	8	0.124	0.073
425-449	43	27	0.231	0.248
450-474	6	19	0.032	0.174
475-499	2	10	0.011	0.092
500-524	0	5	0.000	0.046
525-549	0	0	0.000	0.000
550-574	1	3	0.005	0.028
575-599	0	0	0.000	0.000
600 and over	0	1	0.000	0.005
Totals	186	110	1	1

Figure 8-6, Counts and Probabilities for Horsepower Bins By Model Year Category

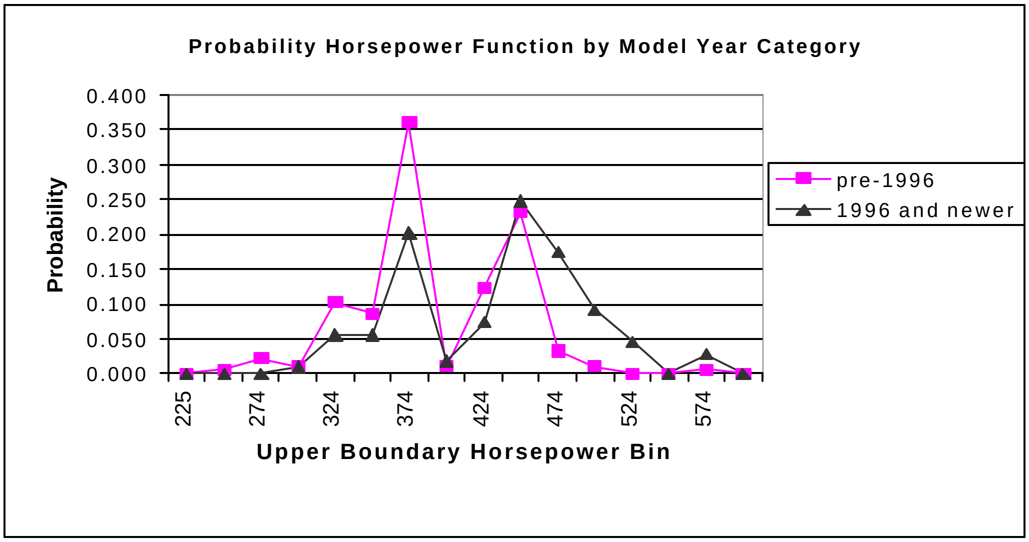


Figure 8-7, Probability Density Functions of Horsepower Distributions by Model Year Category

8.1.4 Supplemental Horsepower Comparisons

The surveys conducted at the weigh stations incorporated more detailed data than the surveys conducted at the truckstops. The expanded data of the weigh stations include origin-destination data, truck company type, and truck body type. These three categories are statistically analyzed to determine if there is a relationship between the variables and engine horsepower distributions. However, because these data were collected from only four weigh stations, the results of this section can not be confirmed without collecting data from additional locations.

8.1.4.1 Origin-Destination

Long-haul trips may have higher engine horsepower than short haul trucks to provide a higher level of driver comfort for the longer driving distance. The origin-destination variable is disaggregated into four trip types: internal-internal (II) trips, internal-external (IX) trips, external-internal (XI) trips, and external-external (XX) trips. Internal and external are defined relative to the 13 county study area. However, because the Douglas County weigh station is the only weigh station inside the study area, it is the only location capable of generating internal-internal trips. As mentioned in the previous sections, the data collected at this location was collected 1½ years prior to the other weigh station data, and therefore has an older fleet that corresponds to lower engine horsepower. Therefore, to avoid correlation between older internal trips and horsepower, the trip type data are disaggregated into the two model year categories: 1) pre-1996 and 2) 1996-1999.

Figures B-5 and B-6 show the contingency tables for the pre-1996 and the 1996-1999 horsepower distributions respectively. For the pre-1996 model year trucks, the χ^2 value for the crosstab analysis is (11.9) lower than the 5% significance value of the χ^2 distribution for 9 degrees of freedom (15.5). Therefore, there is no statistically significant correlation between the horsepower collected with different trip types for this model year category.

For 1996 and newer model year trucks, the χ^2 value for the crosstab analysis is (17.8) which is greater than the 5% significance value of the χ^2 distribution for 9 degrees of freedom (15.5). These results indicate that there is a relationship between trip type and horsepower distributions. However, because the number of internal-internal trips is only 2, the crosstab results can not be confirmed without additional data.

8.1.4.2 Truck Company Type

Truck company types can be divided into two categories: private and for-hire companies. For-hire companies may have higher horsepower engines to allow for a wide range of shipping activity to match the variety of companies that utilize for-hire companies. The contingency table for the crosstab analysis for these two categories is shown in Figure B-7. The χ^2 value for the crosstab analysis (7.5) is slightly lower than the 5% significance value of the χ^2 distribution for 3 degrees of freedom (7.8). Therefore, there is a possible correlation between truck type and horsepower.

Because, there are only two truck company categories, it is possible to examine the points of departure for the two distributions. The for-hire companies have more high horsepower trucks, while the private companies have more low horsepower trucks. As mentioned earlier, for-hire companies may require a higher engine horsepower to provide flexibility in shipping patterns. However, because of the small number of private truck companies included in the sample, more data are needed before this variable can be fully incorporated into a horsepower model.

8.1.4.3 Truck Body Type

The truck body type was disaggregated into six categories based on external features that can be identified during roadside surveys: closed containers, flatbeds, open containers, car carriers, tankers, and dump trucks. However, only the closed container and flatbed body types had sufficient readings to enable the use of crosstab analysis. The flatbed truck is a body type often associated with hauling large machinery and heavy materials, and is therefore a potential body type with higher horsepower than other body types.

The contingency table for these two categories is shown in Figure B-8. The χ^2 value for the crosstab analysis is 7.6 which is slightly lower than the 5% significance value of the χ^2 distribution for 3 degrees of freedom (7.8). This indicates that more data would be useful to determine if the body type category were related to horsepower distributions.

8.1.5 Summary of Horsepower Comparisons

Each of the three supplemental variables (trip type, company type, and body type) indicates that additional data would be beneficial to determine if these variables can be statistically correlated to horsepower distributions. The comparisons between survey location and horsepower distributions indicate that there is not a statistically significant difference between horsepower and Interstate location. Engine horsepower was found to be highly correlated with model year. The final horsepower model was developed based on two model year categories: 1) pre-1996 model year trucks and 2) 1996-1999 model year trucks.

8.2 Summary of Gross Vehicle Weight Data and Modeling

Portable WIM equipment was used to collect data at five locations in the Atlanta metropolitan area (see Figure 7-1 for map). Four of the data collection locations were on the Interstate legs where differences in weight distributions are likely to occur as described in Chapter 7. The fifth location was inside the perimeter freeway where through truck trips are legally restricted. Over 75,000 heavy-duty vehicles from the four heavy-duty vehicle classifications are included in the following analyses.

These vehicles are initially divided based on the vehicle classification format developed during the preliminary truck surveys (Chapter 5). The existence of statistically significant temporal fluctuations in the weight distributions are determined using crosstab analysis. Factors associated with night time truck travel such as increased driver salary, reimbursement of hotel expenses, and increased security requirements for overnight trips result in increased night time shipping costs. Therefore, only extremely valuable commodities and time-sensitive commodities are shipped at night. These temporal differences in shipping costs likely result in different shipping patterns by time of day. The time periods were established in Chapter 6 as follows:

1) midday time period, 9:00AM – 3:00PM,
2) afternoon time period, 3:00PM – 7:00PM, and
3) night time period, 7:00PM – 9:00AM.

Increased costs are also associated with weekend shipping due primarily to the required increased compensation to truck drivers for working. Accordingly, day-of-week time periods are generally categorized as weekday and weekend. However, final weight models may include time periods that overlap both weekdays and weekends.

The temporal analysis will establish time periods that have unique weight distributions. For each time period, the weight distribution is compared between all five data collection locations to verify that there is no spatial variability as specified in the assumptions of this research (Chapter 7).

8.3 Weight Distribution of Class 9 Trucks

Trucks with 5 axles and 1 trailer (noted as Class 9 trucks) are between 70-90% of all truck traffic on the Interstate system in Georgia. Characterizing the weight distribution of this truck classification is a major step towards understanding the weight distribution of the entire truck fleet. The weight distribution for the entire data set for Class 9 trucks is shown in Figure 8-8.

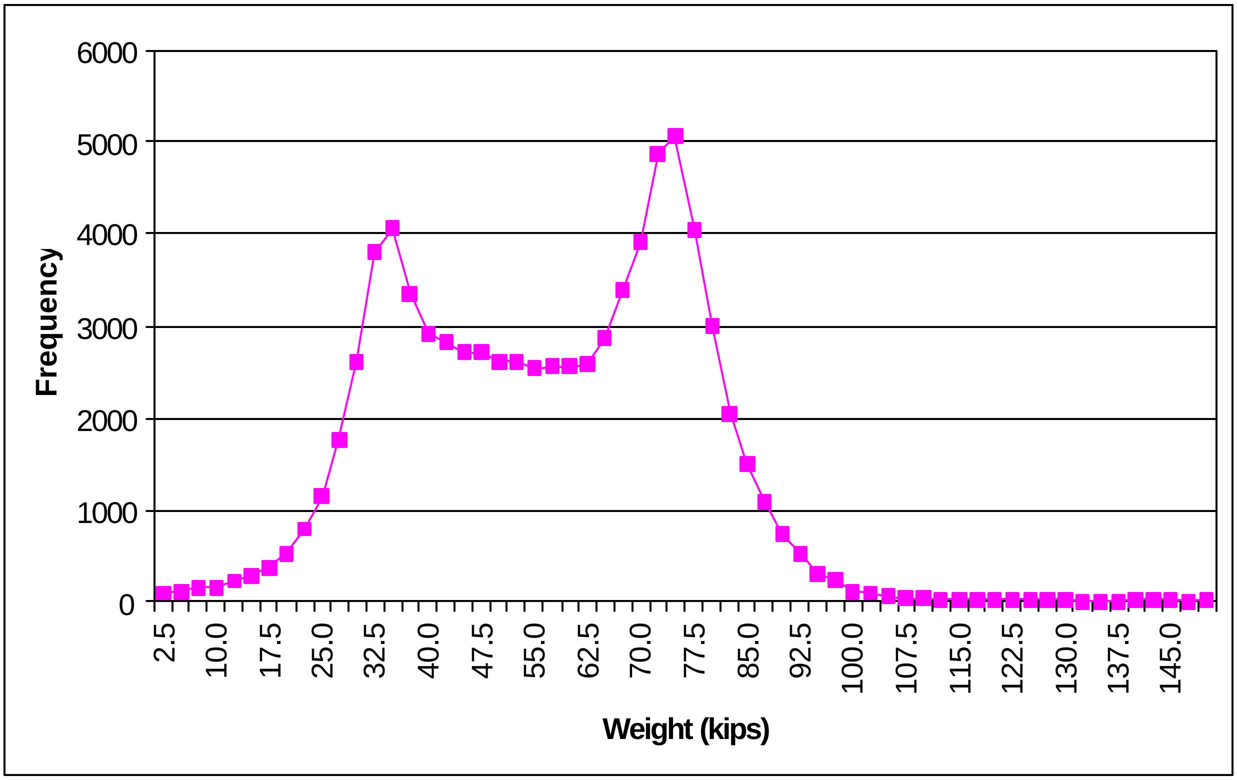


Figure 8-8: Weight Distribution of All Class 9 Trucks, All Time Periods, All Locations

8.3.1 Weight Distributions for Midday Time Period

The midday time period (9:00AM to 3:00PM) has the largest volume of truck activity. 22,507 trucks were included in the development of the midday truck model for Class 9 trucks. Figure B-9 shows the contingency table for the weight distribution of this data set based on 5,000 pound weight bins and each day of the week. The weight bin category upper and lower limits were condensed from the standard 30,000 and 90,000 pounds to 40,000 and 70,000 pounds due to the existence of a significant amount of noise in between the weight bins of the highest and lowest weight bin classifications.

The χ^2 value of the corresponding contingency table (Figure B-10) is 162.0 which is much higher than the 1% significance level for the χ^2 value for a distribution with 42 degrees of freedom which is approximately 65. Careful observation of the contingency table reveals that the weekend data have some of the highest daily χ^2 values indicating that they are likely from a different distribution. For example, the Sunday χ^2 value is 77.6 which is almost half of the 162.0 χ^2 value for the entire table.

Therefore, a second contingency table is created (Figure B-11) with only the weight data from Monday to Friday. The χ^2 value of this new contingency table drops to 55.5 with a corresponding χ^2 value for a distribution of 28 degrees of freedom at 48.3 at the 1% significance level. Figure B-11 also shows that the Monday weight data have the highest daily χ^2 values indicating that they are likely from a different distribution. By removing Monday from the data set, and performing an analysis on the Tuesday through Friday data, the χ^2 value drops to 36.5 which is below the χ^2 value at the 1% significance level of 38.9 (Figure B-12). Therefore, there is no statistically significant difference between the midday weight distributions of Class 9 vehicles on Tuesday, Wednesday, Thursday, or Friday. These four days can be combined to form a single unique weight distribution: Tuesday-Friday, midday distribution for Class 9 trucks.

Additional crosstab analyses are performed for the remaining 3 days (Saturday, Sunday, and Monday) to determine if any of these days can be combined to form unique distributions. Figure B-13 shows the χ^2 value table comparing Saturday and Sunday weight distributions. The χ^2 value from the contingency table of 26.7 is less than the χ^2 value for 13 degrees of freedom which is 27.7 indicating that the Saturday and Sunday weight distributions do not have statistically significant differences. These two days form a single unique weight distribution: Saturday and Sunday, midday distribution for Class 9 trucks.

The formation of the two weight distributions above incorporates six of the seven days of the week for the midday time period. This leaves Monday as the third and final unique weight distribution during this time period. The combined analyses result in the creation of three distributions for the midday time period: 1) Tuesday-Friday, 2) Monday, and 3) Saturday and Sunday. Figures 8-11 and 8-12 show the graphical and numerical representations of these three weight distributions based on the percentage of trucks expected in each weight bin. The higher weights associated with weekend truck travel is likely a result of increased shipping costs of weekend trucks. While the higher percentage of empty trucks associated with the Monday weight distribution, is possibly the result of a re-distribution of truck fleets from dispatch centers to pickup and delivery locations on Mondays.

	Weight Ranges (000s pounds)								
	< 40	40-45	45-50	50-55	55-60	60-65	65-70	> 70	Total
Mondays	0.374	0.075	0.058	0.050	0.057	0.055	0.074	0.256	1
Tuesdays -Fridays	0.334	0.071	0.063	0.061	0.059	0.058	0.083	0.272	1
Saturdays /Sundays	0.262	0.064	0.067	0.075	0.067	0.075	0.099	0.291	1

Figure 8-9, Numerical Representation of Class 9 Midday Weight Model

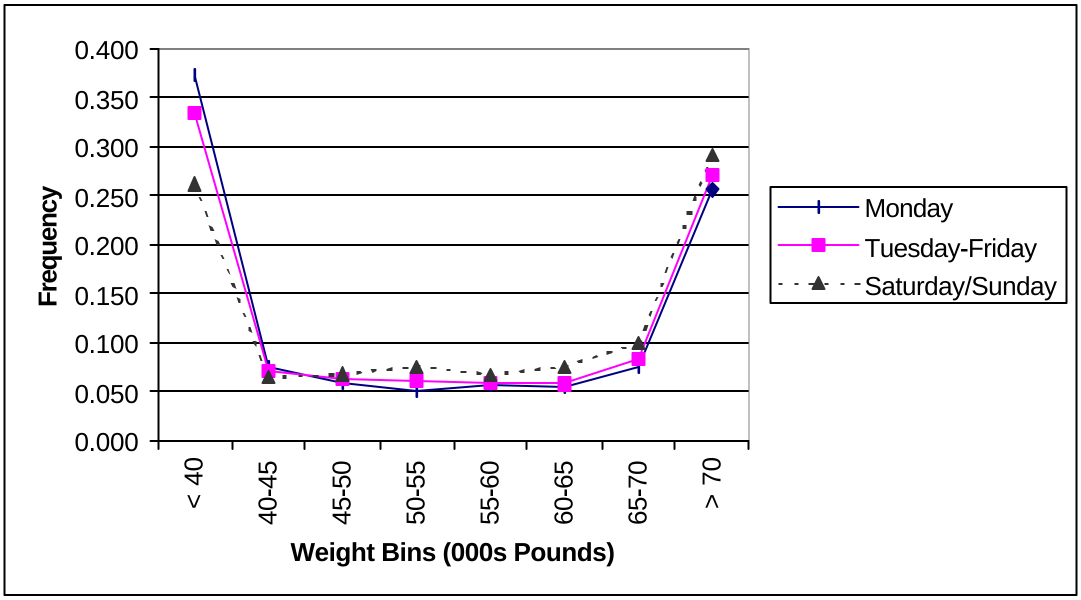


Figure 8-10, Graphic Representation of Midday Time Period Weight Distributions, Class 9 Trucks

8.3.2 Weight Distributions for Afternoon Time Period

Figure B-14 shows the χ^2-value table for the day of week and each weight bin for the afternoon time period (3:00PM-7:00PM). The χ^2 value from the contingency table of 321 is much higher than the χ^2-value with 78 degrees of freedom of approximately 110. Unlike the midday time period, Figure B-14 shows that there is not a particular day which dominates the χ^2 value total of 321.

Therefore, the χ^2-value total is primarily a result of variation between weight bin categories and secondarily a result of the variation between day-of-week categories. The noise between weight bins can potentially be reduced through decreasing the number of bins. Therefore, for the afternoon time period analysis, the bins are reduced to three categories: 1) trucks less than 40,000 pounds (empty trucks), 2) trucks between 40,000 and 65,000 pounds (less than truckload trucks), and 3) trucks over 65,000 pounds (full trucks). Crosstab analysis using these three bins produce a contingency table as shown in Figure B-15. The χ^2 value from the contingency table is 68.4 which is still much higher than 26.2 which is the χ^2 value with 12 degrees of freedom at the 1% significance level.

The majority of the 68.4 χ^2-value is from Sunday while the values for the other days of the week are much lower. Therefore, a new contingency table with Monday through Saturday is created with χ^2 values shown in Figure B-16. The χ^2 value of this table is 14.4 which is much lower than the 21.7 χ^2 value with 10 degrees of freedom at the 1% significance level. This indicates that there is no statistically significant difference between weight distributions for the six days from Monday through Saturday.

Therefore, the weight data collected during these six days can be combined into a single unique weight distribution for the afternoon time period. Sunday will have a separate and unique weight distribution for the afternoon time period. The final weight models for the distribution are based on these two day-of-week categories: 1) Monday through Saturday, and 2) Sunday as shown numerically in Figure 8-11 and graphically in Figure 8-12. Similar to the midday time period, the differences between the two distributions are likely the result of the increased shipping costs associated with Sunday shipping resulting in a higher percentage of full trucks on Sunday.

	Weight Ranges (000s pounds)			
	< 40	40-65	> 65	Total
Monday-Saturday	0.309	0.327	0.363	1
Sunday	0.231	0.334	0.435	1

Figure 8-11, Numerical Model of Afternoon Weight Distributions, Class 9 Trucks

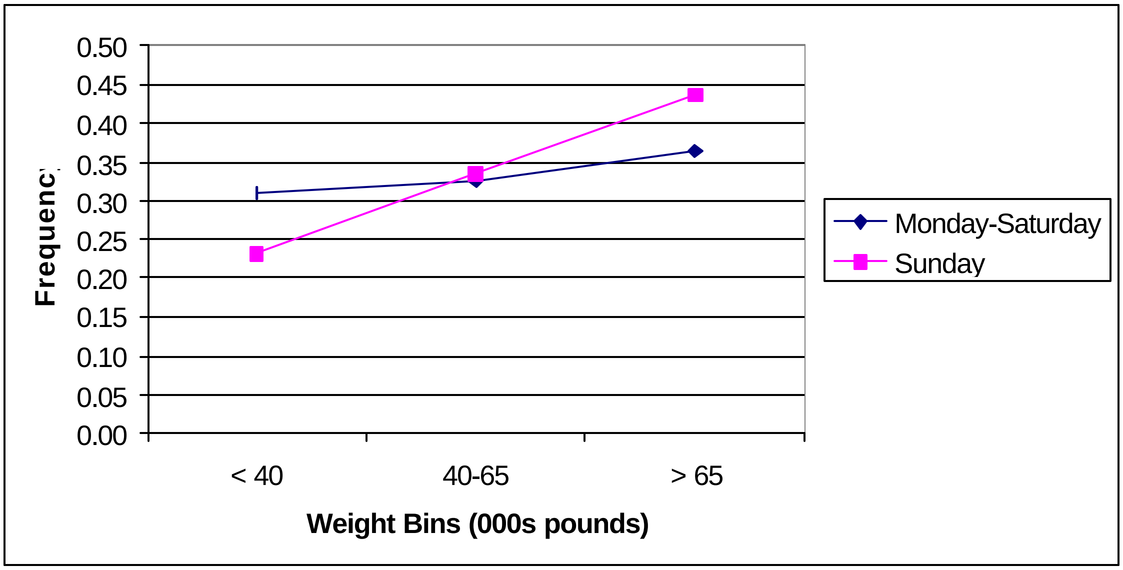


Figure 8-12, Graphic Model of Afternoon Weight Distributions, Class 9 Trucks

8.3.3 Weight Distributions for Night Time Period

Figure B-17 shows the χ^2 values for the contingency table for the nighttime weight distributions (between 7:00PM and 9:00 AM) by day of week and 5,000 pound weight bins. The χ^2 value of the contingency table is 314.5, considerably higher than the χ^2 value of 78 degrees of freedom at the 1% significance level of approximately 110. After condensing the weight bins to the three used in the afternoon analysis and removing several different combinations of days of the week, no suitable day-of-week distributions could be statistically substantiated for the nighttime distribution.

One possible reason for this is that differences in weight distribution by locations have affected the corresponding total distribution. To check for this possibility, a contingency table is developed for the nighttime data by location using the three weight bins as shown in Figure B-18. The χ^2 value of the contingency table is 169.8 which is much higher than the 16.8 value for 6 degrees of freedom at the 1% significance level confirming that there are differences in weight distributions at different locations. Therefore, for the night time period there is a statistically significant relationship between location and weight distributions. For the night time period, a single weight distribution model can not be developed to represent the entire metropolitan area. It is likely that a more complex weight model including spatial characteristics and origin-destination information will need to be developed to model truck weights during the night time period. Verification of the independence between location and weight distribution for the midday and afternoon time periods is performed in the following section.

8.3.4 Verification of Independence Between Location and Weight Distribution

One of the primary assumptions of this research is that the weight distribution of a particular class of truck is identical throughout the metropolitan region. Crosstab analyses are performed on each of the midday and afternoon weight models to determine if there is a relationship between the data collection location and the weight distribution (Figured B-19 to B-23). Each model is disaggregated by as many of the five locations for which significant data were collected: I-20 Douglas County, I-75 Clayton County, I-75 Cobb County, I-85 Airport, and I-75 Howell Mill Road. For each of the contingency tables, the χ^2 value is lower than the corresponding χ^2 value at the 1% significance level as shown below in Figure 8-13. These results indicate that for the midday and afternoon time periods, weight distributions can not be considered statistically different. Therefore, the models developed for these time periods in sections 8.3.1 and 8.3.2 are statistically validated.

Day of Week	Time Period	X2 Cont. Table	X2 Dist. (1% level)	Location Matters
Tuesday-Friday	9:00AM-3:00PM	17.88	20.09	No
Monday	9:00AM-3:00PM	13.75	16.81	No
Saturday, Sunday	9:00AM-3:00PM	18.65	20.09	No
Monday-Saturday	3:00PM-7:00PM	14.88	20.09	No
Sunday	3:00PM-7:00PM	13.63	16.81	No

Figure 8-13, Chi-square Values of Contingency Tables and from Chi-square Distribution

8.4 Weight Distributions for Class 10-13 Trucks

The weight distribution of Class 10-13 trucks is fairly normally distributed. Figure 8-14 shows the shape of the distribution of all trucks with either more than 5 axles or more than 1 trailer. Using Chi-square analysis and the three weight bins used for much of the Class 9 data analysis, this weight distribution was disaggregated into 3 time periods:

1) 9:00AM – 7:00PM, Monday – Sunday,

2) 7:00PM – 9:00AM Tuesday – Sunday, and

3) 7:00PM – 9:00AM on Mondays.

Figures B-24 and B-25 show the contingency tables for the first two of these three distributions, while Figure 8-15 shows the χ^2 value of the contingency table compared to that of the χ^2 value distribution with the appropriate degrees of freedom at the 1% significance level. The results of the contingency tables indicate that there is no statistically significant difference between each of the three time periods. Therefore, the development of three separate and unique time periods is justified.

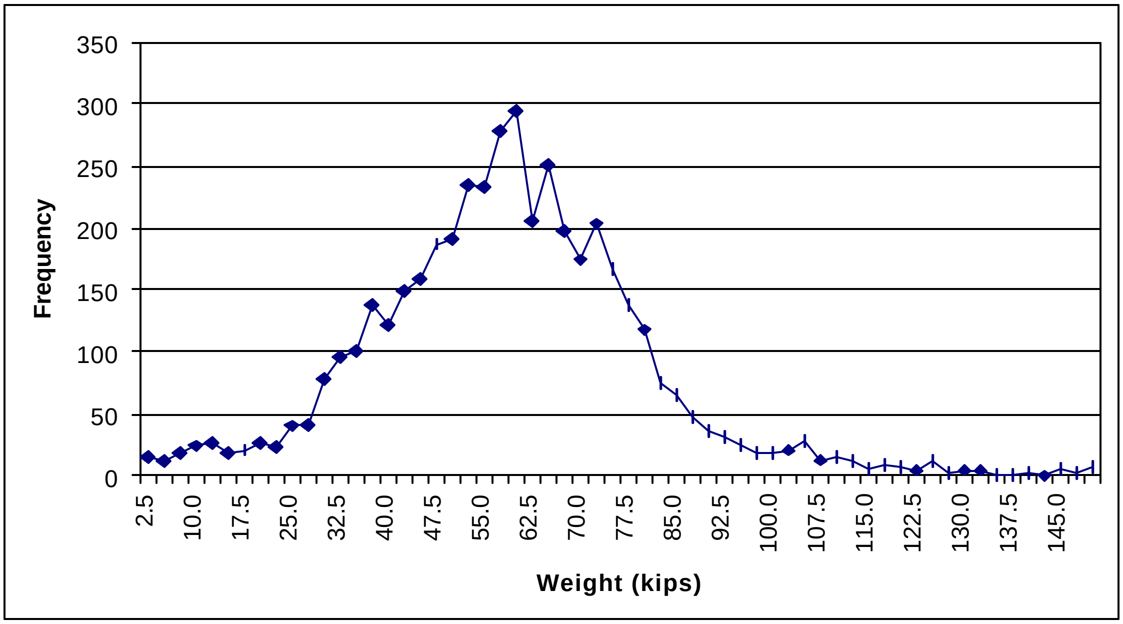


Figure 8-14, Weight Distribution for Class 10-13 Trucks

Time of Day	Day of Week	Contingency Table Chi-Square	Distribution Chi-Square
9:00AM – 7:00PM	Mondays – Sundays	33.0	40.3
7:00PM – 9:00AM	Tuesdays – Sundays	20.0	23.2

Figure 8-15, Chi-Square Values by Time Period, Class 10-13 Trucks

8.4.1 Verification of Independence Between Location and Weight Distributions

To check that the distributions are equivalent at different locations, crosstab analysis was performed for each of the three distributions. The contingency tables for each distribution is shown in Figures B-26 to B-28, while Figure 8-16 (below) shows the χ^2 values of the contingency tables compared to the χ^2 value of the distributions for the appropriate amount of degrees of freedom at the 1% significance level. The results of these analyses confirm that the data collection location does not have a statistically significant relationship with the weight distributions developed for Class 10-13 trucks. Therefore, the distributions can be applied throughout the Atlanta metropolitan area.

Time of Day	Day of Week	Contingency Table Chi-Square	Distribution Chi-Square	Location Matters
9:00AM – 7:00PM	Mondays - Sundays	8.8	26.2	No
7:00PM – 9:00AM	Tuesdays - Sundays	15.1	23.2	No
7:00PM – 9:00AM	Mondays	6.6	63.7	No

Figure 8-16, Chi-Square Values by Location, Class 10-13 Trucks

8.5 Weight Distribution of Class 6-7 Trucks

The shape of the composite Class 6-7 truck distribution was found to have two peaks, similar to the Class 9 truck weight distribution. Figure 8-19 shows the weight distribution of all Class 6-7 trucks at all locations during all time periods.

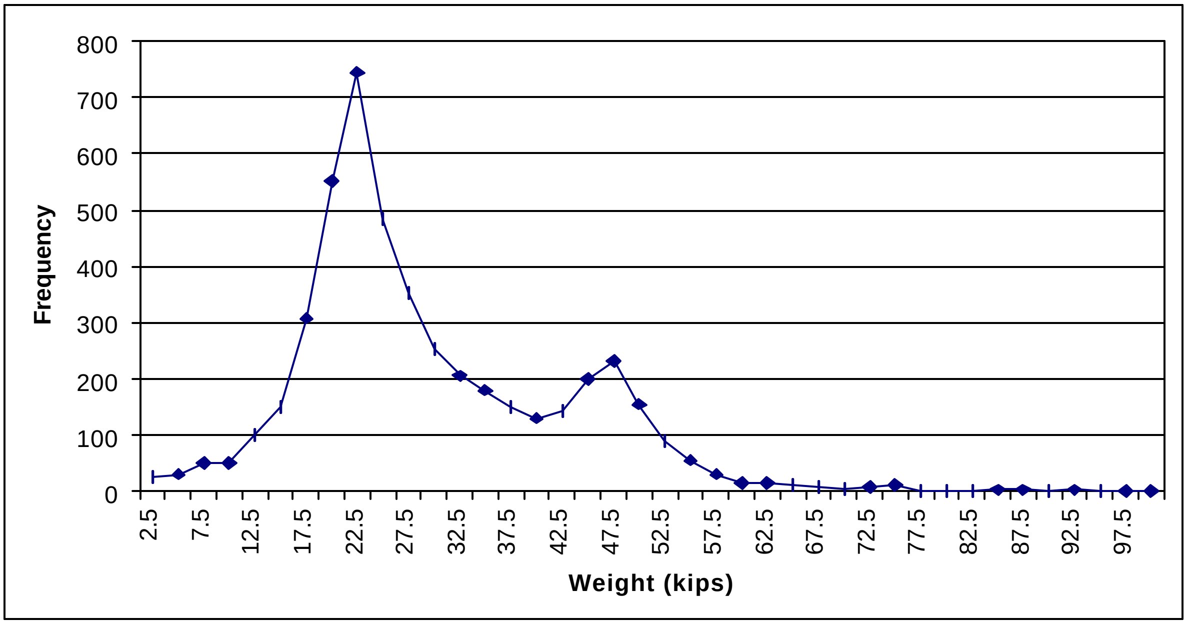


Figure 8-17, Weight Distribution, All Class 6-7 Trucks

However, using crosstab analysis the weight distribution of Class 6-7 trucks at I-75 near Howell Mill Rd. (inside the perimeter freeway) was found to be statistically different than the other locations during all time periods. In particular, there is a noticeable lack of trucks with weights greater than 40,000 pounds. However, all the data collected at locations outside the perimeter have similar distributions. Therefore, the analysis of Class 6-7 trucks will be constrained to locations outside the perimeter. More data must be collected to determine the nature of the differences for the weight distributions of Class 6-7 trucks on the Interstate system inside the perimeter.

Using crosstab analysis the weight distribution of Class 6-7 trucks on the Interstate "legs" was disaggregated into 4 time periods:

1) 9:00AM – 3:00PM, Mondays, Tuesdays, and Fridays,
2) 9:00AM – 3:00PM Wednesdays and Thursdays,
3) 3:00PM – 7:00PM Mondays – Sundays, and
4) 7:00PM – 9:00AM Mondays-Saturdays.

The weight bins used for this analysis were empty or lightly loaded trucks (less than 30,000 pounds), partially loaded trucks (between 30,000 and 40,000 pounds), and full trucks (greater than 40,000 pounds).

Figures B-29 to B-32 show the contingency tables for each of these four distributions. Figure 8-18 (below) shows the χ^2 values of the contingency table compared to that of the χ^2 values from the distribution with the appropriate degrees of freedom at the 1% significance level. For each of the four time periods the contingency table value is less than the distribution value indicating that there is no statistically significant difference between the day-of-week categories for each of the time periods. Therefore, each of these four distributions can be considered to be separate and unique models for Class 6-7 trucks.

Time of Day	Day of Week	Contingency Table Chi-Square	Distribution Chi-Square
7:00PM – 9:00AM	Tuesdays – Fridays	14.6	20.1
3:00PM – 7:00PM	Mondays - Sundays	22.4	26.2
9:00AM – 3:00PM	Mondays, Tuesdays, and Fridays	11.8	13.2
9:00AM – 3:00PM	Wednesdays and Thursdays	7.6	9.2

Figure 8-18, Chi-Square Values by Time Period, Class 6-7 Trucks

8.5.1 Verification of Independence Between Location and Weight Distributions

To check that the distributions are equivalent at different locations (excluding Interstate 75 Howell Mill Rd.), chi-square analysis was performed for each of the four distributions. The contingency tables for each distribution is shown in Figures B-33 to B-36, while Figure 8-19 (below) shows the χ^2 values of the contingency tables compared to the χ^2 value of the distributions for the appropriate amount of degrees of freedom at the 1% significance level. For each of the four time periods the contingency table value is less than the distribution value indicating that there is no statistically significant difference between the location and the weight distribution for each of the time periods. This confirms the independence of location and weight distribution for each of the four Class 6-7 trucks models.

Time of Day	Day of Week	Contingency Table Chi-Square	Distribution Chi-Square	Location Matters
7:00PM – 9:00AM	Tuesdays – Fridays	15.0	16.8	No
3:00PM – 7:00PM	Mondays – Sundays	10.4	26.2	No
9:00PM – 3:00PM	Mondays, Tuesdays, and Fridays	2.1	13.3	No
9:00PM – 3:00PM	Wednesdays and Thursdays	6.8	9.2	No

Figure 8-19, Chi-Square Values by Location, Class 6-7 Trucks

8.6 Weight Distribution of Class 8 Trucks

The shape of the composite Class 8 truck distribution resembles a truncated normal distribution. Due to the overlap of reading two closely spaced passenger cars as a 4-axle, 2-unit truck, all vehicles recorded as less than 20,000 pounds in this classification were removed from the distribution. Figure 8-20 shows the weight distribution of all Class 8 trucks at all locations during all time periods.

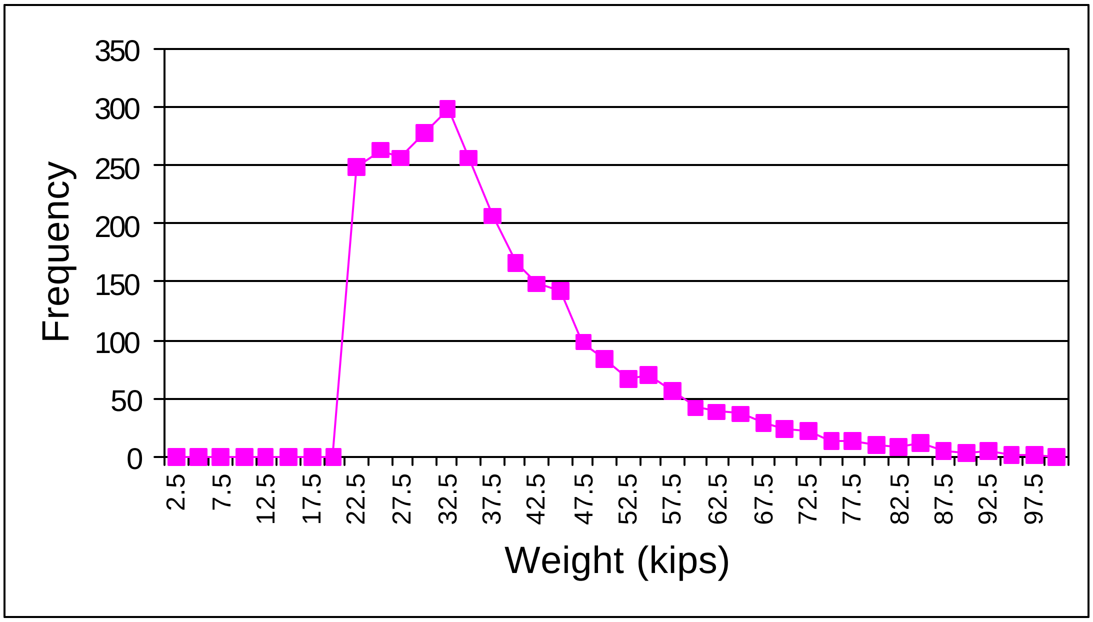


Figure 8-20: Weight Distribution for All Class 8 Trucks

Two weight bins are used for this analysis: the first for empty trucks (less than 40,000 pounds), and the second for loaded trucks (more than 40,000 pounds). Using crosstab analysis, this weight distribution was disaggregated into 5 time periods:

1) 9:00AM – 3:00PM, Mondays – Fridays,
2) 9:00AM – 3:00PM Saturdays,
3) 3:00PM – 7:00PM Mondays – Fridays,
4) 3:00PM - 7:00PM Saturdays, and
5) 7:00PM – 9:00AM Mondays - Saturdays.

Insufficient quantities of data were collected to create weight distributions for all time periods not included in this disaggregation.

Figures B-37 to B-39 show the contingency tables for the three distributions with more than one day of the week. Figure 8-21 (below) shows that the χ^2 value of the contingency table is lower than the χ^2 value from the distribution with the appropriate degrees of freedom at the 1% significance level for each time period. Therefore, the day of week range for each of these time periods is not statistically different from other days in the range. The distributions developed for each of the five time periods can be considered as separate and unique weight distribution models for Class 8 trucks.

Time of Day	Day of Week	Contingency Table Chi-Square	Distribution Chi-Square
9:00AM – 3:00PM	Mondays – Fridays	7.1	13.3
3:00PM – 7:00PM	Mondays – Fridays	6.3	13.3
7:00PM – 9:00AM	Mondays – Saturdays	6.2	15.1

Figure 8-21, Chi-Square Values by Time Period, Class 6-7 Trucks

8.6.1 Verification of Independence Between Location and Weight Distributions

To check that the distributions are equivalent at different locations, crosstab analysis was performed for each of the five distributions. The contingency table for each distribution is shown in Figures B-40 to B-43. Figure 8-22 (below) shows that the χ^2 values of the contingency tables are lower than the χ^2 value of the distributions for the appropriate amount of degrees of freedom at the 1% significance level, except for the 3:00PM -7:00PM time period during the weekdays. In particular, the data collected on

Interstate 85 near the airport have a much higher percentage of loaded trucks than the other locations. Therefore, no model can be developed for the weight distribution of Class 8 trucks during the afternoon time period.

However, there is no statistically significant relationship between location and weight distribution for the other three time periods. Therefore, the assumption of the lack of relationship between location and distribution is verified for these time periods, and the models can be included in the final weight model set.

Time of Day	Day of Week	Contingency Table Chi-Square	Distribution Chi-Square	Location Matters
9:00AM – 3:00PM	Mondays – Fridays	9.1	13.3	No
3:00PM – 7:00PM	Mondays – Fridays	114.4	13.3	Yes
7:00PM – 9:00AM	Mondays – Saturdays	9.8	13.3	No
9:00AM – 3:00PM	Saturdays	0.11	9.21	No

Figure 8-22, Chi-Square Values by Location, Class 8 Trucks

8.7 Weight Distribution Model of 2/1 Trucks

Although no method was successful in determining an efficient post-processing method for 2-axle trucks, it is notable that the weight distribution for this classification appear to be normally distributed. This shape is apparent in data collected exclusively at weigh station scales and from any set of 3-hour distributions collected with the portable WIM equipment. This shape is similar to that of Class 8 and Class 10-13 trucks and indicates that future research into weight distributions of Class 5 trucks must be made without use of a peak-shifting method.

8.8 Summary of Truck Weight Models

The method of dividing the onroad truck fleet into vehicle classes and developing weight distributions based on unique time periods was successful in generating several statistically significant models. Most notably, weight distributions were developed for the Class 9 vehicles that dominate the Interstate truck fleet during the midday and afternoon time periods that are most important for emissions modeling. More data must be collected to develop models for the time periods which exhibited significant differences due to variability in weight distributions based on fluctuations by day-of-week or location.

The truck weight models are summarized in Figures 8-23 through 8-27. The values in each of the bins represent the estimated fraction of trucks for a given time period in the particular weight range.

	Weight Ranges (000s pounds)								
	< 40	40-45	45-50	50-55	55-60	60-65	65-70	> 70	Total
Mondays	0.374	0.075	0.058	0.050	0.057	0.055	0.074	0.256	1
Tuesdays -Fridays	0.334	0.071	0.063	0.061	0.059	0.058	0.083	0.272	1
Saturdays /Sundays	0.262	0.064	0.067	0.075	0.067	0.075	0.099	0.291	1

Figure 8-23, Numerical Models of Midday Time Period Weight Distributions, Class 9 Trucks

	Weight Ranges (000s of pounds)				
Day of Week	Time of Day	< 40	40-65	> 65	Totals
Monday-Saturday	3:00PM – 7:00PM	0.309	0.327	0.363	1
Sunday	3:00PM – 7:00PM	0.231	0.334	0.435	1
All	7:00PM-9:00PM	0.226	0.377	0.397	1
All	6:00AM-9:00AM	0.225	0.323	0.452	1

Figure 8-24, Numerical Models of Weight Distribution for Afternoon and Night Time Periods, Class 9 Trucks

	Weight Bins (000s of pounds)				
Day of Week	Time of Day	< 40	40-65	> 65	Totals
All	9:00AM – 7:00PM	0.185	0.384	0.431	1
Tuesdays – Sundays	7:00PM – 9:00AM	0.171	0.534	0.294	1

Figure 8-25, Numerical Models of Weight Distributions for Class 10-13 Trucks

	Weight Bins (000s of pounds)				
Day of Week	Time of Day	< 30	30 - 40	> 40	Totals
Mon., Tues., and Fridays	9:00AM – 3:00PM	0.539	0.177	0.284	1
Wednesdays, Thursdays	9:00AM - 3:00PM	0.610	0.233	0.157	1
All	3:00PM - 7:00PM	0.542	0.193	0.265	1
Tuesdays – Saturdays	7:00PM-9:00AM	0.609	0.221	0.170	1

Figure 8-26, Numerical Models of Weight Distribution for Class 6-7 Trucks

Time Periods		Weight Bins (000s of pounds)		
Day of Week	Time of Day	< 40	> 40	Totals
Mondays – Fridays	9:00AM - 3:00PM	0.801	0.182	1
Saturdays	9:00AM - 3:00PM	0.683	0.317	1
Mondays – Fridays	3:00PM - 7:00PM	0.677	0.323	1
Mondays – Saturdays	7:00PM - 9:00AM	0.595	0.405	1

Figure 8-27, Numerical Models of Weight Distribution for Class 8 Trucks

8.8.1 Confidence Intervals

Confidence intervals for each of the models are calculated for the given time period for data collected on one day. Therefore, the confidence interval for the fraction of Class 9 trucks which are less than 40,000 pounds between Tuesdays and Saturdays during the midday time period refers to data collected on one particular day (such as the Wednesday midday time period) and not data collected over the four-day time period.

The confidence intervals for each of the numerical models are shown in Figures 8-28 through Figures 8-32. Only 3 of the 64 confidence intervals, and none of the confidence intervals for the Class 9 trucks, are greater than 0.100 indicating that the models developed in this research are relatively robust.

	Weight Ranges (000s pounds)							
Day of Week	< 40	40-45	45-50	50-55	55-60	60-65	65-70	> 70
Mondays	0.071	0.071	0.015	0.015	0.010	0.020	0.019	0.030
Tuesdays-Fridays	0.016	0.005	0.006	0.006	0.005	0.005	0.007	0.018
Saturdays/Sundays	0.051	0.012	0.014	0.015	0.014	0.011	0.014	0.027

Figure 8-28, Confidence Intervals of Midday Time Period Weight Distributions, Class 9 Trucks

	Weight Ranges (000s of pounds)			
Day of Week	Time of Day	< 40	40-65	> 65
Monday-Saturday	3:00PM – 7:00PM	0.021	0.025	0.023
Sunday	3:00PM – 7:00PM	0.076	0.052	0.079
All	7:00PM-9:00PM	0.020	0.023	0.029
All	6:00AM-9:00AM	0.031	0.02	0.026

Figure 8-29, Confidence Intervals of Weight Distribution for Afternoon and Night Time Periods, Class 9 Trucks

	Weight Bins (000s of pounds)			
Day of Week	Time of Day	< 40	40-65	> 65
All	9:00AM – 7:00PM	0.069	0.053	0.050
Tuesdays – Sundays	7:00PM – 9:00AM	0.073	0.123	0.132

Figure 8-30, Confidence Intervals of Weight Distributions for Class 9-13 Trucks

	Weight Bins (000s of pounds)			
Day of Week	Time of Day	< 30	30 – 40	> 40
Mon., Tues., and Fridays	9:00AM – 3:00PM	0.096	0.030	0.098
Wednesdays, Thursdays	9:00AM - 3:00PM	0.068	0.039	0.050
All	3:00PM - 7:00PM	0.060	0.185	0.529
Tuesdays – Saturdays	7:00PM-9:00AM	0.064	0.032	0.047

Figure 8-31, Confidence Intervals of Weight Distribution for Class 6-7 Trucks

Time Periods		Weight Bins (000s of pounds)	
Day of Week	Time of Day	< 40	> 40
Mondays – Fridays	9:00AM - 3:00PM	0.041	0.041
Saturdays	9:00AM - 3:00PM	0.267	0.267
Mondays – Fridays	3:00PM - 7:00PM	0.061	0.061
Mondays – Saturdays	7:00PM - 9:00AM	0.065	0.065

Figure 8-32, Confidence Intervals of Weight Distribution for Class 8 Trucks

Chapter 9

9. CONCLUSION ON HEAVY-DUTY VEHICLE EMISSIONS MODELS

The development of onroad truck horsepower and weight distributions contributes to the implementation of heavy-duty vehicle emissions models. Heavy-duty vehicles within a particular engine horsepower classification are thought to have constant gram per brake-horsepower-hour emission rates. This dissertation has developed onroad weight and horsepower distributions on the metropolitan level that can be incorporated into regional emissions estimation. These distributions are a significant addition to the truck data inventory. Previous truck weight studies have focused on gathering statewide information for pavement management, and engine horsepower data have not been collected in any truck surveys.

This research has developed the following four important findings on the development of weight and horsepower distributions for a metropolitan area:

1) an axle-trailer classification format is an effective method of categorizing vehicles for both horsepower and weight models,
2) representative heavy-duty vehicle horsepower distributions can be developed from roadside truck surveys,
3) for the Atlanta metropolitan area, engine horsepower and vehicle weight are not statistically correlated for a particular axle-trailer classification, and

4) representative heavy-duty vehicle weight distributions can be developed through post-processing portable WIM equipment data.

9.1 Heavy-Duty Vehicle Classification

The classification technique used in this research is a five-vehicle classification system based on axle-trailer configurations. Each vehicle class is a grouping of one or more of the FHWA 16-vehicle classification system:

1) 5-axle, 1-trailer vehicles (FHWA Class 9),
2) vehicles with either more than 5 axles or more than 1 trailer (FHWA Class 10-13),
3) 3 or 4 axle, 1-trailer vehicles (FHWA Class 8),
4) 3 or 4 axle, single-unit vehicles (FHWA Class 6 and 7), and
5) 2-axle, single-unit vehicles (FHWA Class 5).

This five-class heavy-duty vehicle classification methodology was found to be sufficient in explaining variability in truck weight distributions throughout the Atlanta metropolitan area and horsepower distributions at the Douglas County weigh station. Compatibility of the five-class system with the FHWA 16-vehicle classification system allows for the development of weight and horsepower distributions using existing truck count data for a freeway segment. The use of a five-class axle-trailer classification system also enables flexibility for future field data collection by allowing class data to be collected without interfering in traffic. It also reduces the difficulty in collecting field data across a large number of classes as is necessary for the current FHWA system that includes 9 truck classes from the 16-vehicle classification scheme.

The five-vehicle classification system used in this research is also compatible with roadside and commercial vehicle survey data. The majority of roadside truck surveys, which are generally used to obtain cordon-level truck data, already include a data item for axle-trailer configuration. Commercial vehicle surveys, which are generally used to obtain metropolitan-level truck travel demand estimates, generally include a mailout-mailback survey instrument. These surveys can easily include a data item which requests the most frequent axle-trailer configuration over the lifetime of a tractor, or the particular axle-trailer combination of each individual truck trip. The inclusion of axle-trailer vehicle classification data in current and future truck data collection efforts allows for the estimation of truck weight distributions and horsepower distributions on the metropolitan level when combined with the models developed in this research.

9.2 Heavy-Duty Vehicle Horsepower Data Collection

Due to the data collection constraints of truck surveys at weigh stations and truckstops, the examination of truck horsepower distributions was limited to a combined Class 9 and Class 10-13 truck classification during the midday hours on weekdays. This combined classification reflects approximately 70% of the overall Interstate truck fleet, but a much smaller percentage of the overall truck fleet for a metropolitan area during the weekday, daytime time period that is likely to produce the highest and most critical emissions for air quality. Future truck data collection efforts could collect truck horsepower data from the other classes through a combination of mailout-mailback surveys and updated national truck data acquired through detailed studies such as the UMTRI study (Blower et al, 1988).

The truck horsepower data indicate that there is no spatial variability in truck horsepower distributions for the Atlanta metropolitan area. The truck horsepower data collected at nine separate locations produced distributions that could not be statistically distinguished using crosstab analysis. However, a strong correlation between the model year of the truck and horsepower was established. Horsepower was found to be generally increasing with model year, and in particular a large increase in the average horsepower is noticeable for trucks with 1996 and newer model years. The final model relates horsepower to model year based on two model year categories (pre-1996 and 1996-1999) as shown in Figure 8-7.

Limited data on trip type (internal or external), truck company type (private or for-hire), and truck body type (container of flatbed) were also analyzed to establish the relationship of these variables with horsepower. Only truck body type appeared to yield a possible statistical correlation based on the data collected. Flatbed trucks appear to have higher mean engine horsepower than container trucks. However, only 21 flatbed trucks were included in this comparison, so more data are needed to confirm this relationship.

9.3 Relationship Between Weight and Horsepower

Data from the truck surveys were also utilized to determine the relationship between horsepower and gross vehicle weight. The results indicate that for the entire truck fleet, there is a correlation between the two variables. However, when the data are disaggregated by four vehicle dasses (combining Class 9 and Class 10-13 into one class), the horsepower is independent of gross vehicle weight. For the three classes with less than 5 axles, these results are limited to the Douglas County weigh station. For the combined Class 9 and Class 9-13 truck classification, the results can be generalized to represent the entire Interstate system in the metropolitan area during weekday, daytime hours based on the numerous surveys implemented at several locations. The independence of truck weights and horsepower is important because it provides the basis for creating separate models for truck weights and truck horsepower.

9.4 Heavy-Duty Vehicle Weight Data Collection

Portable weigh-in-motion equipment along with temporary onroad loops and sensors were used to collect weight data to maximize the flexibility of site selection for the truck weight sampling plan. However, the use of this type of exposed onroad equipment increases the error due to temperature sensitivity from the WIM equipment. The temperature sensitivity varied at different sites likely due to differences in surface conditions and minor differences in equipment installation. The complexity of the relationship between temperature and the raw WIM weight readings hindered the ability to apply traditional temperature sensitive adjustment factors to the equipment readings. Therefore, a post-processing method was developed based on known locations of peaks in the weight distributions of the 5-axle combination vehicles and 3-axle single-unit vehicles. This post-processing method allowed for the development of accurate weight distributions for all classes of vehicles except the 2-axle trucks.

The methodology for truck weight site selection is based on the assumption that spatial variability is negligible for truck weight distributions throughout a metropolitan area. Four of the five data collection sites were selected to be on the Interstate segments that are close to the boundaries of the Atlanta 13-county metropolitan area. This site selection maximizes the possibility of capturing differences in weight distributions based on known differences in rural weight distributions from data at rural truck weigh stations.

Weight distributions were developed for each temporal period based on chi-square comparisons developed from crosstab contingency tables. For Class 9 vehicles during the midday time period, a model was developed with highly disaggregated weight categories. However, due to limited numbers of trucks sampled for other class and time period combinations, a smaller range of weight categories was often utilized, most notably: empty trucks, partially loaded trucks, and full trucks. Each of the time-specific and class-specific weight distributions developed using the crosstab analysis was then statistically checked to verify the validity of the assumption of spatial uniformity in weight distributions. Single distributions are disaggregated by into five distributions based on the five portable WIM data collection locations, and a crosstab analysis is performed to determine if there are statistically significant differences between locations.

Weight distributions that were verified to have no spatial variability are included in the final weight distribution model set.

The majority of weight distributions were found to have no spatial variability, but the exceptions to this assumption include Class 9 trucks between 7:00PM and 9:00AM and Class 8 trucks inside the perimeter freeway relative to outside the perimeter freeway. The nighttime variability in Class 9 truck weight distributions is a possible result of the increase in long haul trips combined with the decreased nighttime volume. These factors increase the ability of a single commodity or industry to dominate the truck fleet of a particular route resulting in a spatially-variable truck weight distribution.

Class 8 truck weight variability is possibly based on differences between trip type for trucks inside and outside the perimeter. Truck trips inside the perimeter include a higher percentage of short range trips than other freeway segments based on legal restrictions of through truck trips from using the Interstates inside the perimeter and road geometry that limits the benefits of through truck trips using these freeways. Spatial variability of Class 8 trucks indicates that a model including factors such as local land use characteristics will likely assist in estimating weight distributions for this truck classification throughout a metropolitan area.

The shapes of the distributions for each vehicle class reveal a significant amount of information about how the trucks of a particular classification are utilized. For example, 5-axle, 1-trialer trucks (noted as Class 9 trucks) have two very distinct peaks near 35,000 and 75,000 pounds regardless of location or time of day that the data are collected. This indicates that a significant amount of the trucks in this classification travel either completely empty (represented by the peak near 35,000 pounds) or completely full (represented by the peak near 75,000 pounds). However, trucks with either more than 5 axles or more than 1 trailer (noted as Class 10-13 trucks), had a weight distribution which resembles a normal distribution with a mean near 55,000 pounds well below the 80,000 pound federal legal limit. This indicates that Class 10-13 trucks often travel with less than truck load shipments.

Single-unit trucks with 3 or more axles (noted as Class 6-7 trucks) have weight distributions which are bi-modal similar to the Class 9 trucks but with a much smaller "full truck" peak than Class 9 trucks. This indicates that a relatively small fraction of this classification of trucks is affected by the weight limits. A much higher percentage are traveling either empty or with light loads. For example, a dump truck can be full by volume, but still very far from the 48,000 pound legal weight limit for 3-axle trucks depending upon the density of the material it is carrying.

Double-unit trucks with 3 or 4 axles have a very different weight distribution than their single-unit counterparts. Trucks in this class tend to have weights that are normally distributed with means near 30,000 pounds. This weight is very close to the empty truck weight of approximately 25,000 pounds with very few trucks weighing near the legal maximums of 48,000 and 64,000 pounds for 3 and 4 axle trucks respectively. This matches with interviews of regional truck companies that indicated that these trucks are used for local pickup and delivery. These trucks specialize in the scheduled, less than truckload local shipping market and are often either empty or very lightly loaded reflecting their status as being primarily in between pickups and deliveries.

Temporal variability was found to be an important factor in truck weight distribution variability for each classification. Generally, truck weights were found to be heavier during nighttime and weekend periods. This may reflect the increase in driver and/or truck operator cost in operating during off-peak work periods, in addition to the delivery of high percentage of shipments to meet early morning schedules. Trucks that have recently delivered a shipment and are either empty or LTL tend to have more flexibility in arrival times and therefore travel during the low cost daytime, midday time period.

For each of the truck classes, there is a possible link between vehicle weight and other vehicle characteristics such as vehicle length. This is likely to be a productive area of future research that can assist in the development of more detailed weight distributions for each vehicle classification. The relationship between vehicle length and vehicle weight is also likely to be correlated to the temporal variability found in the models of this research. For example, the models developed in this research indicate that nighttime 3-axle trucks are generally heavier than daytime 3-axle trucks. This increase in weights is likely partially due strictly to time period differences in weight distributions, but part of the increase might be predicted based on an increased vehicle length of the nighttime 3-axle truck fleet relative to the daytime 3-axle truck fleet. Developing models in this fashion, truck weights could potentially be generated for a particular roadway using vehicle classification, temporal variability, and vehicle length.

9.5 Limitations of Research

There are three primary sources of limitations from the final models developed in this research: 1) limitations based on the data collection equipment, 2) limitations based on the data collection methodology, and 3) limitations based on the model development technique. Data collection equipment limitations for the truck weight data include the restriction on truck weight data collection to the far right lane of traffic at all portable WIM locations. Therefore, the truck weight models reflect truck weights for that lane of traffic and ignore any differences that may exist between trucks in different lanes. Theoretically, this limitation could be perceived as problematic due to the possibility that a higher percentage of local truck trips use the right lane to increase accessibility to on-ramps and off-ramps.

However, at the Douglas County site, virtually all of the trucks traveled in the right lane during the daytime and weekday time periods in order to prepare to enter the weigh station. The data collected during the midday, weekday time periods at the Douglas County location were not determined to be statistically different than the data collected at the other locations during the same time period. This implies that the lane of traffic is not a factor for truck weight distributions. The 2-lane data of Douglas County data were found to be similar to the 1-lane data at other locations during most time periods.

The data collection methodology incorporated only Atlanta metropolitan area locations. Therefore, much more data needs to be collected in order to gauge the transferability of the horsepower and weight models to other metropolitan areas. It is particularly crucial that metropolitan areas determine the applicability of the lack of spatial relationship with truck weight distributions. If specific locations in a metropolitan area are known to be dominated by a particular industry or land use type (i.e. ports or concentrated industrial areas), then separate models may be necessary for different regions. Alternatively, a weight model that accounted for local land use variability can be developed.

The use of axle-trailer configuration for the overall modeling process is likely applicable to other metropolitan areas. This classification scheme allows for the incorporation of data with existing and future data sources. In addition, the classification format can be easily compared to results in other metropolitan areas to determine the nature of differences between regions.

The use of temporal variation as a primary determinant in truck weight modeling is also likely transferable to other metropolitan areas. Truck counts are known to vary in similar fashions across different metropolitan areas based on shipping costs and time-sensitivity of goods. Variability in weight distributions by temporal periods is likely a result of the same factors. Therefore, it should be expected that truck weights increase in other metropolitan areas during night time periods similar to truck weights in Atlanta.

For truck engine horsepower, additional data needs to be collected to verify the transferability of the model year to horsepower relationship to other metropolitan areas. An initial step in this process is to compare the horsepower distributions of this research with national engine sales data. If these horsepower distributions are found to be statistically equivalent, then national engine horsepower data can likely be used in other metropolitan areas on freeway segments that do not have unique truck fleets. The relationship between model year and horsepower will also likely assist in explaining differences that do exist between metropolitan areas, differences between short range and long range truck trips, and differences on non-freeway road types.

All data collected in this research were for trucks using the Interstate system. This is a major limitation preventing the application of the results throughout a metropolitan area. Therefore, to extend the models to other road classifications, it will be necessary to perform similar portable WIM studies and truck horsepower surveys on other road types such as arterials and local roads.

The model development technique employed throughout this research relies on chi-square testing of one sample with two variables using contingency tables. This is a useful tool for determining the uniqueness of multiple distributions. However, for distributions that are found to be different, this technique does not identify the particular point of departure for the distributions, except for the case when only two distributions are being compared. Therefore, for distributions where spatial differences were identified the specific reason for the difference is not statistically indicated.

The use of contingency tables decreased the ability of the models to measure the specific frequency of truck characteristics that are likely to produce particularly high emission levels such as extremely low horsepower and extremely high weight. Due to the low numbers of readings in these bins, they were generally combined with adjacent bins to create bin values sufficient to allow for chi-square comparisons across several distributions. In addition, for distributions where bin sizes are adjusted, numerous bin combinations are possible that were not specifically tested for the models developed in this research.

9.6 Incorporation into Heavy-Duty Vehicle Emissions Models

The estimation of heavy-duty vehicle emissions involves three primary components: heavy-duty engine emission rate estimation, heavy-duty vehicle activity estimates, and the estimation of heavy-duty vehicle fleet characteristics. This research has provided disaggregated models for estimating characteristics of truck weight and horsepower. Onroad truck weight and engine horsepower are two variables that will be instrumental in the truck fleet characterization portion of heavy-duty vehicle emissions models.

Portable WIM equipment was found to be a sufficient method to collect a large quantity of truck weight data when combined with the proper post-processing method. Truck surveys were found to be effective for collecting a combination of truck horsepower, weight, and origin-destination data for the classification of trucks which predominates the Interstate network.

On-going research in heavy-duty engine emissions along with improvements in heavy-duty vehicle activity are also needed to more accurately estimate truck emissions. This research will allow for more efficient characterization of heavy-duty engines for future in-use engine testing. The weight and horsepower models when used in combination with on-going improvements in speed-acceleration data will create a more representative distribution of loads applied to engines. This research can also guide the development of future metropolitan-level commercial vehicle surveys to include the full range of heavy-duty vehicle fleet characteristics in the surveyed samples. The inclusion of the temporal and spatial aspects of the truck weight and horsepower distributions will allow for the incorporation of these data items into the emerging disaggregated mobile emissions models.

APPENDIX A

ACCURACY OF PORTABLE WIM DATA

The raw weight readings of the portable WIM equipment can be inaccurate based on a number of factors, most notably compression by the WIM electronics, temperature sensitivity of the onroad equipment, an internal algorithm, and random error. Several methods have been developed to calibrate WIM equipment, but the methods vary with the type of equipment used and the primary vehicle class of concern for weight data collection (Wu, 1996; Papagiannakis et al., 1996; Dahlin, 1992; Fekpe et al., 1992; ASTM 1990). A comprehensive calibration method has not yet been developed for portable weigh-in-motion equipment used in conjunction with temporary loops and sensors.

The standard method for dealing with equipment inaccuracy is to develop factors to account for each of the sources of inaccuracy and adjust the weight readings on an individual basis according to the derived factors. The Douglas County weigh station would be an ideal location to develop these factors based on the ability to compare the station's highly accurate static and weigh-in-motion truck scales to readings collected on the portable WIM. However, a sufficient range of temperature readings can not be collected as a result of the limited operating hours of the weigh station to daytime hours. Therefore, the manual peak shifting (MPS) method of post-processing the raw readings from the portable WIM was developed based on known locations of peaks in Class 9 and Class 6-7 weight distributions (Chapter 6). The accuracy of the MPS post-processing method is measured in this Appendix.

A portable WIM site was installed ¼ mile upstream of the Douglas County weigh station to enable comparison of the portable WIM weight readings with the Douglas County weigh station readings. The readings from this site are also used to confirm the systematic compression of the raw readings of the portable WIM equipment and to determine the appropriateness of the manual peak-shifting (MPS) post-processing method. Data were collected on nearly 300 vehicles across four classes of trucks over seven separate days. Figure A-1 lists the dates, times, and number of vehicles sampled by truck classification for each day of data collection at the Douglas County site.

Weight readings for individual vehicles were recorded by placing one data collector next to the portable WIM equipment, and one data collector next to the Douglas County weigh station WIM scale. Through the use of two-way radios, trucks were identified from the onroad fleet by the data collector at the portable WIM site and communicated to the data collector at the weigh station WIM. Both the portable WIM and station WIM weights were recorded by each data collector and checked for accuracy at the office. Using this WIM site, raw weight readings from individual vehicles at the WIM site could be compared directly with readings from the weigh station WIM.

DATE	Time	Class 5 Trucks Sampled	Class 6-7 Trucks Sampled	Class 8 Trucks Sampled	Class 9-13 Trucks Sampled
1/23	12:00PM-2:00PM	8	3	3	26
1/25	3:00PM-4:00PM	6	3	3	6
1/27	3:00PM-4:00PM	16	16	13	36
2/3	2:15PM-3:30PM	14	11	15	8
2/5	12:00PM-3:00PM	14	9	14	5
2/8	12:30PM-3:00PM	17	10	9	9
2/9	3:30PM-7:30PM	23	0	0	0
TOTAL		98	52	57	90

Figure A-1: Classification, Dates, Times, and Number Sampled for Trucks Included in MPS Accuracy Test

The individual raw data readings were post-processed using the MPS method as outlined in Chapter 6. Figures A-2 through A-5 list the weight readings for each of the vehicles included in the data collection process. Each record includes the survey date, survey identification number, the specific vehicle axle-trailer configuration, and the three weight readings. The first column titled 'PWIM wt' lists the raw weight reading from the portable WIM. The second column titled 'MPS wt' lists the post-processed weight based on the manual peak shifting calculation method outlined in Chapter 6. The last column titled 'Doug wt' lists the weight reading from the Douglas County weigh station in-motion scale.

Date	ID No	Ax	Units	PWIM wt	MPS wt	Doug wt
1/23/99	1	5	2	61.3	61.0	33.2
1/23/99	2	5	2	66.6	67.6	36.8
1/23/99	3	5	2	47.6	43.9	39.7
1/23/99	4	5	2	58.2	57.1	56.0
1/23/99	6	5	2	72.4	74.9	75.5
1/23/99	7	5	2	60.4	59.9	59.8
1/23/99	9	5	2	73.5	76.3	71.9
1/23/99	10	5	2	41.8	36.6	32.9
1/23/99	11	5	2	67.3	68.5	71.1
1/23/99	12	5	2	60.5	60.0	56.1
1/23/99	15	5	2	68.8	70.4	72.6
1/23/99	17	5	2	45.9	41.8	33.2
1/23/99	19	5	2	51.3	48.5	36.4
1/23/99	20	5	2	35.1	28.3	33.5
1/23/99	22	5	2	50.6	47.6	41.3
1/23/99	24	5	2	49.8	46.6	45.5
1/23/99	25	5	2	83.6	88.9	78.4
1/23/99	27	5	2	75.6	78.9	77.3
1/23/99	28	5	2	76.4	79.9	79.2
1/23/99	29	5	2	48.4	44.9	37.3
1/23/99	34	5	2	48.0	44.4	37.4
1/23/99	35	5	2	55.8	54.1	51.9
1/23/99	36	5	2	68.2	69.6	72.1
1/23/99	39	5	2	58.5	57.5	60.3
1/23/99	40	5	2	50.1	47.0	45.5
1/23/99	41	5	2	43.6	38.9	39.5
1/25/99	1	5	2	52.2	56.0	47.4
1/25/99	2	5	2	54.5	58.1	53.2
1/25/99	3	5	2	70.5	73.1	81.5
1/25/99	13	5	2	35.4	40.2	28.7
1/25/99	14	5	2	57.9	61.3	74.1
1/25/99	16	5	2	30.6	35.7	63.2
1/25/99	18	5	2	49.9	53.8	64.4
1/25/99	23	5	2	25.4	30.8	38.3
1/25/99	24	5	2	24.6	30.1	38.0
1/25/99	30	5	2	22.4	28.0	29.4
1/27/99	1	6	2	72.4	90.1	n/a
1/27/99	2	5	2	55.4	61.2	62.1
1/27/99	3	6	2	50.6	53.0	71.4
1/27/99	12	6	2	59.9	68.8	70.5
1/27/99	18	5	3	43.9	41.6	62.3
1/27/99	19	5	2	39.9	34.8	37.3
1/27/99	20	6	2	68.3	83.1	71.4
1/27/99	21	5	2	66.4	79.9	80.1
1/27/99	22	5	2	35.9	28.0	31.8
1/27/99	25	5	2	60.6	70.0	72.2
1/27/99	28	5	2	52.9	56.9	54.9
1/27/99	33	5	2	62.0	72.4	76.6
1/27/99	35	5	2	32.1	21.6	24.2
1/27/99	36	5	2	63.0	74.1	72.2
1/27/99	38	6	2	40.3	35.5	38.0
1/27/99	40	5	2	38.7	32.8	29.6
1/27/99	41	5	2	47.0	46.9	46.6
1/27/99	42	5	2	44.9	43.3	32.1
1/27/99	43	5	2	37.4	30.6	33.0
1/27/99	44	5	2	39.4	34.0	35.4
1/27/99	45	5	2	37.6	30.9	31.8
1/27/99	47	5	2	48.9	50.1	47.9
1/27/99	48	5	2	36.2	28.5	30.4
1/27/99	52	5	2	44.1	42.0	40.3
1/27/99	53	5	2	46.0	45.2	41.7
1/27/99	55	5	2	66.5	80.1	81.2

Figure A-2 Raw, Post-Processed, and Station WIM Weights for Class 9-13 Trucks

Date	ID No.	Ax.	Units	PWIM wt	MPS wt	Doug Wt
1/27/99	56	6	2	57.9	65.4	75.2
1/27/99	57	6	2	82.4	107.1	93.0
1/27/99	58	5	2	60.2	69.3	65.5
1/27/99	60	5	2	36.6	29.2	32.3
1/27/99	63	5	2	60.4	69.7	71.2
1/27/99	68	5	2	43.1	40.3	31.0
1/27/99	69	5	2	63.8	75.5	82.3
1/27/99	70	6	3	61.4	71.4	59.4
1/27/99	71	5	2	42.0	38.4	39.2
1/27/99	72	5	2	43.2	40.4	39.3
1/27/99	77	6	2	63.2	74.4	71.2
2/3/99	1	6	2	81.6	86.9	89.3
2/3/99	3	5	3	61.2	58.0	54.2
2/3/99	4	5	3	77.1	80.5	78.8
2/3/99	14	5	3	62.4	59.7	63.1
2/3/99	24	5	2	45.8	36.1	36.9
2/3/99	29	5	2	69.1	69.1	72.3
2/3/99	30	5	2	57.7	53.0	47.6
2/3/99	40	6	3	70.6	71.3	64.5
2/3/99	44	5	3	61.3	58.1	56.1
2/5/99	1	5	3	47.6	53.3	34.8
2/5/99	3	6	2	52.4	59.2	69.3
2/5/99	6	6	2	57.3	65.1	60.2
2/5/99	7	5	2	31.9	34.3	32.1
2/5/99	9	5	3	43.8	48.7	56.6
2/8/99	2	6	2	50.8	66.1	72.2
2/8/99	3	5	2	44.1	54.7	43.8
2/8/99	4	5	2	42.9	52.7	52.9
2/8/99	16	5	2	30.1	30.9	32.5
2/8/99	21	5	2	39.0	46.1	43.4
2/8/99	22	5	2	44.2	54.9	61.7
2/8/99	27	5	3	37.8	44.0	44.0
2/8/99	30	5	2	28.6	28.4	27.9

Figure A-2 (cont’d) Raw, Post-Processed, and Station WIM Weights for Class 9-13 Trucks

Date	ID No.	Ax	Units	PWIM wt	MPS wt	Doug wt
1/23/99	13	3	1	26.7	24.4	20.3
1/23/99	18	3	1	35.6	34.3	28.7
1/23/99	31	3	1	29.6	27.6	20.4
1/25/99	5	3	1	24.9	26.6	22.5
1/25/99	6	3	1	28.2	30.2	29.3
1/25/99	7	3	1	43.7	47.4	45.8
1/25/99	9	3	1	28.0	30.0	23.1
1/25/99	22	3	1	13.0	13.3	18.6
1/25/99	27	3	1	24.2	25.8	43.1
1/25/99	28	3	1	24.4	26.0	44.1
1/27/99	6	3	1	27.7	26.4	21.8
1/27/99	7	3	1	25.6	23.4	21.5
1/27/99	9	3	1	23.9	20.9	21.8
1/27/99	11	3	1	27.9	26.6	23.5
1/27/99	13	3	1	31.7	32.1	34.2
1/27/99	16	3	1	40.9	45.2	49.2
1/27/99	17	3	1	14.9	8.1	15.7
1/27/99	23	3	1	28.7	27.8	25.5
1/27/99	24	3	1	22.2	18.5	20.6
1/27/99	30	3	1	40.6	44.8	42.3
1/27/99	31	3	1	18.9	13.8	n/a
1/27/99	46	3	1	36.3	38.6	45.2
1/27/99	59	3	1	39.5	43.2	45.6
1/27/99	64	3	1	27.7	26.4	24.9
1/27/99	66	3	1	38.0	41.1	19.5
1/27/99	78	3	1	23.0	19.6	17.5
1/27/99	79	3	1	31.8	32.2	30.3
2/3/99	6	3	1	53.5	54.2	45.6
2/3/99	10	3	1	26.0	23.6	20.2
2/3/99	12	3	1	42.0	41.4	38.1
2/3/99	20	3	1	31.2	29.4	20.8
2/3/99	25	3	1	42.8	42.3	34.2
2/3/99	26	3	1	33.4	31.8	32.9
2/3/99	27	3	1	26.0	23.6	20.1
2/3/99	33	3	1	22.6	19.8	17.5
2/3/99	36	3	1	36.8	35.6	34.0
2/3/99	39	3	1	50.6	50.9	48.9
2/3/99	46	3	1	44.8	44.5	43.6
2/5/99	2	3	1	21.5	21.1	20.8
2/5/99	8	3	1	36.3	42.2	40.2
2/5/99	10	3	1	32.1	36.2	43.8
2/5/99	12	3	1	35.2	40.6	45.0
2/5/99	13	3	1	37.5	43.9	47.1
2/5/99	15	3	1	38.4	45.2	43.2
2/5/99	19	3	1	25.7	27.1	23.4
2/5/99	26	3	1	33.4	38.1	44.9
2/5/99	36	3	1	23.8	24.3	22.2
2/8/99	7	3	1	21.8	25.5	23.6
2/8/99	8	3	1	18.8	20.5	20.8
2/8/99	12	3	1	31.9	42.3	44.8
2/8/99	13	3	1	19.1	21.0	18.9
2/8/99	17	3	1	18.2	19.5	19.0
2/8/99	25	3	1	29.0	37.5	34.7
2/8/99	28	3	1	33.6	45.2	43.9
2/8/99	41	3	1	15.9	15.7	27.8
2/8/99	42	3	1	33.0	44.2	44.0
2/8/99	43	3	1	19.8	22.2	21.4

Figure A-3 Raw, Post-Processed, and Station WIM Weights for Class 6-7 Trucks

Date	ID No.	Ax	Units	PWIM wt	MPS wt	Doug wt
1/23/99	16	4	2	44.3	43.9	43.8
1/23/99	26	4	2	21.7	18.8	17.5
1/23/99	38	4	2	51.3	51.7	52.0
1/25/99	10	3	2	33.5	36.1	35.3
1/25/99	12	4	2	30.0	32.2	25.5
1/25/99	19	3	2	15.5	16.1	26.5
1/25/99	26	4	2	19.1	20.1	33.1
1/25/99	31	4	2	25.1	26.8	49.0
1/27/99	5	4	2	33.4	34.5	29.4
1/27/99	27	4	2	30.0	29.6	29.1
1/27/99	32	3	2	24.0	21.1	23.2
1/27/99	50	4	2	29.3	28.6	n/a
1/27/99	51	4	2	44.6	50.5	51.4
1/27/99	54	4	2	46.1	52.6	51.5
1/27/99	61	4	2	28.8	27.9	28.1
1/27/99	62	4	2	36.6	39.1	37.5
1/27/99	76	4	2	48.1	55.5	57.5
1/27/99	82	3	2	23.3	20.1	21.1
1/27/99	87	3	2	28.9	28.1	28.5
1/27/99	88	4	2	38.0	41.1	40.5
1/27/99	89	3	2	25.4	23.1	25.0
1/27/99	90	3	2	26.3	24.4	25.4
2/3/99	2	3	2	29.0	26.9	25.5
2/3/99	5	4	2	35.9	34.6	29.7
2/3/99	9	4	2	37.4	36.3	29.9
2/3/99	13	3	2	28.6	26.5	28.1
2/3/99	16	4	2	39.8	38.9	29.2
2/3/99	17	4	2	35.3	33.9	28.0
2/3/99	18	4	2	54.6	55.4	53.6
2/3/99	21	4	2	40.2	39.4	33.0
2/3/99	23	4	2	43.3	42.8	39.0
2/3/99	31	3	2	35.3	33.9	26.7
2/3/99	34	4	2	54.0	54.7	53.0
2/3/99	41	3	2	34.1	32.6	31.2
2/3/99	42	4	2	45.7	45.5	32.3
2/3/99	45	4	2	51.4	51.8	33.8
2/3/99	50	3	2	32.0	30.3	29.4
2/5/99	11	4	2	30.3	33.6	33.9
2/5/99	14	3	2	30.3	33.6	37.0
2/5/99	17	4	2	38.4	45.2	52.2
2/5/99	20	4	2	28.4	30.9	30.7
2/5/99	21	4	2	39.6	46.9	52.8
2/5/99	22	4	2	25.7	27.1	26.4
2/5/99	27	3	2	21.6	21.2	23.2
2/5/99	29	4	2	28.7	31.3	22.3
2/5/99	30	4	2	27.6	29.8	30.6
2/5/99	31	4	2	28.1	30.5	27.9
2/5/99	33	4	2	25.6	26.9	26.9
2/5/99	37	4	2	23.9	24.5	28.4
2/5/99	38	4	2	28.9	31.6	36.4
2/5/99	39	4	2	28.6	31.2	34.2
2/8/99	10	3	2	20.8	23.8	23.9
2/8/99	18	3	2	20.8	23.8	25.1
2/8/99	23	3	2	17.1	17.7	21.7
2/8/99	24	4	2	29.8	38.8	34.6
2/8/99	33	4	2	28.9	37.3	29.5
2/8/99	34	3	2	20.4	23.2	23.8
2/8/99	39	4	2	22.6	26.8	24.2
2/8/99	40	4	2	25.9	32.3	27.7
2/8/99	44	4	2	27.1	34.3	33.1

Figure A-4 Raw, Post-Processed, and Station WIM Weights for Class 8 Trucks

Date	ID No.	Ax	Units	PWIM wt	MPS wt	Doug wt
1/23/99	8	2	1	16.5	16.5	17.0
1/23/99	33	2	1	17.3	17.3	16.0
1/23/99	14	2	1	17.4	17.4	14.5
1/23/99	37	2	1	18.9	18.9	17.4
1/23/99	5	2	1	19.4	19.4	18.9
1/23/99	32	2	1	21.2	21.2	20.8
1/23/99	43	2	1	21.9	21.9	23.4
1/23/99	21	2	1	24.7	24.7	24.6
1/25/99	25	2	1	8.0	11.8	14.0
1/25/99	17	2	1	8.3	12.1	13.2
1/25/99	20	2	1	8.9	12.7	13.6
1/25/99	29	2	1	9.2	13.0	13.8
1/25/99	15	2	1	12.5	16.3	20.1
1/25/99	11	2	1	17.6	21.4	16.8
1/25/99	21	2	1	17.8	21.6	23.0
1/25/99	8	2	1	19.9	23.7	21.6
1/25/99	4	2	1	22.1	25.9	25.9
1/27/99	10	2	1	9.7	10.6	8.8
1/27/99	15	2	1	12.7	13.6	17.6
1/27/99	26	2	1	13.4	14.3	12.2
1/27/99	49	2	1	15.9	16.8	19.3
1/27/99	74	2	1	16.4	17.3	16.5
1/27/99	39	2	1	16.6	17.5	17.1
1/27/99	8	2	1	16.8	17.7	15.6
1/27/99	75	2	1	17.0	17.9	17.7
1/27/99	83	2	1	17.0	17.9	19.8
1/27/99	84	2	1	17.1	18.0	17.0
1/27/99	81	2	1	17.1	18.0	17.9
1/27/99	67	2	1	17.3	18.2	19.2
1/27/99	86	2	1	18.4	19.3	18.3
1/27/99	29	2	1	18.7	19.6	24.2
1/27/99	80	2	1	20.8	21.7	22.8
1/27/99	65	2	1	21.2	22.1	26.1
2/3/99	37	2	1	14.1	13.1	12.8
2/3/99	28	2	1	15.3	14.3	13.3
2/3/99	22	2	1	15.5	14.5	14.5
2/3/99	49	2	1	17.2	16.2	16.2
2/3/99	35	2	1	17.3	16.3	17.7
2/3/99	7	2	1	17.3	16.3	18.1
2/3/99	15	2	1	17.4	16.4	17.2
2/3/99	43	2	1	17.8	16.8	16.5
2/3/99	48	2	1	18.6	17.6	14.9
2/3/99	19	2	1	18.6	17.6	19.9
2/3/99	38	2	1	19.0	18.0	17.3
2/3/99	32	2	1	19.2	18.2	18.6
2/3/99	47	2	1	20.8	19.8	19.6
2/3/99	8	2	1	25.0	24.0	24.5
2/5/99	25	2	1	10.4	14.2	13.8
2/5/99	18	2	1	12.1	15.9	16.7
2/5/99	42	2	1	12.3	16.1	15.4
2/5/99	4	2	1	12.5	16.3	15.7
2/5/99	35	2	1	13.0	16.8	15.5
2/5/99	16	2	1	13.0	16.8	15.9
2/5/99	34	2	1	13.7	17.5	18.4
2/5/99	5	2	1	14.0	17.8	16.6
2/5/99	40	2	1	14.0	17.8	16.6
2/5/99	41	2	1	14.0	17.8	18.6
2/5/99	28	2	1	14.1	17.9	16.8
2/5/99	32	2	1	14.8	18.6	18.4
2/5/99	24	2	1	15.3	19.1	18.0
2/5/99	23	2	1	20.4	24.2	22.1
2/8/99	31	2	1	11.6	15.4	15.4
2/8/99	35	2	1	11.9	15.7	12.6
2/8/99	38	2	1	11.9	15.7	15.2
2/8/99	6	2	1	13.2	17.0	17.5

Figure A-5 Raw, Post-Processed, and Station WIM Weights for Class 5 Trucks

Date	ID No.	Ax	Units	PWIM wt	MPS wt	Doug wt
2/8/99	9	2	1	13.3	17.1	15.4
2/8/99	14	2	1	13.3	17.1	16.3
2/8/99	45	2	1	13.7	17.5	18.0
2/8/99	36	2	1	13.8	17.6	21.4
2/8/99	19	2	1	13.9	17.7	16.5
2/8/99	26	2	1	14.5	18.3	17.4
2/8/99	29	2	1	14.7	18.5	15.2
2/8/99	1	2	1	14.9	18.7	16.6
2/8/99	5	2	1	14.9	18.7	17.7
2/8/99	11	2	1	15.1	18.9	20.6
2/8/99	37	2	1	16.4	20.2	22.9
2/8/99	20	2	1	17.3	21.1	24.5
2/8/99	32	2	1	18.3	22.1	23.7
2/9/99	1	2	1	13.2	15.1	13.0
2/9/99	2	2	1	13.0	14.9	13.0
2/9/99	3	2	1	12.5	14.4	13.0
2/9/99	4	2	1	12.3	14.2	13.0
2/9/99	5	2	1	12.6	14.5	13.0
2/9/99	6	2	1	15.0	16.9	13.0
2/9/99	7	2	1	12.1	14.0	13.0
2/9/99	8	2	1	12.5	14.4	13.0
2/9/99	9	2	1	12.9	14.8	13.0
2/9/99	10	2	1	12.7	14.6	13.0
2/9/99	11	2	1	13.0	14.9	13.0
2/9/99	12	2	1	12.5	14.4	13.0
2/9/99	13	2	1	12.2	14.1	13.0
2/9/99	14	2	1	13.5	15.4	13.0
2/9/99	15	2	1	13.3	15.2	13.0
2/9/99	16	2	1	13.0	14.9	13.0
2/9/99	17	2	1	12.5	14.4	13.0
2/9/99	18	2	1	11.9	13.8	13.0
2/9/99	19	2	1	12.3	14.2	13.0
2/9/99	20	2	1	12.8	14.7	13.0
2/9/99	21	2	1	15.0	16.9	13.0
2/9/99	22	2	1	15.8	17.7	13.0
2/9/99	23	2	1	12.1	14.0	13.0

Figure A-5 (cont'd) Raw, Post-Processed, and Station WIM Weights for Class 5 Trucks

A.1 Confirmation of Systematic Compression

The use of the MPS method is justified by the systematic compression witnessed in the Cobb County portable WIM raw weight readings compared to the uniformity in the location of the empty and full vehicle peaks of Class 9 trucks at several locations including three Georgia weigh stations. However, it is important to identify this phenomenon at an individual site to confirm that it is a feature of the portable WIM equipment. For the two largest data sets of Class 9-13 vehicles (collected on January 23 and January 27th), the error in the portable WIM raw weight readings relative to the weigh station readings are compared to the portable WIM readings (See Figures A-6 and A-7). For unbiased data, the graphs would not show any trend in the data throughout the span of the x-axis. However, for both of these data sets there is a clear downward trend in the data. This provides additional evidence that there is compression in the data sets. The trucks with low weights are underestimated and the trucks with heavy weights are overestimated. This phenomenon creates the compressed weight distributions exhibited in the raw weight readings from the portable WIM site on I-75 in Cobb County.

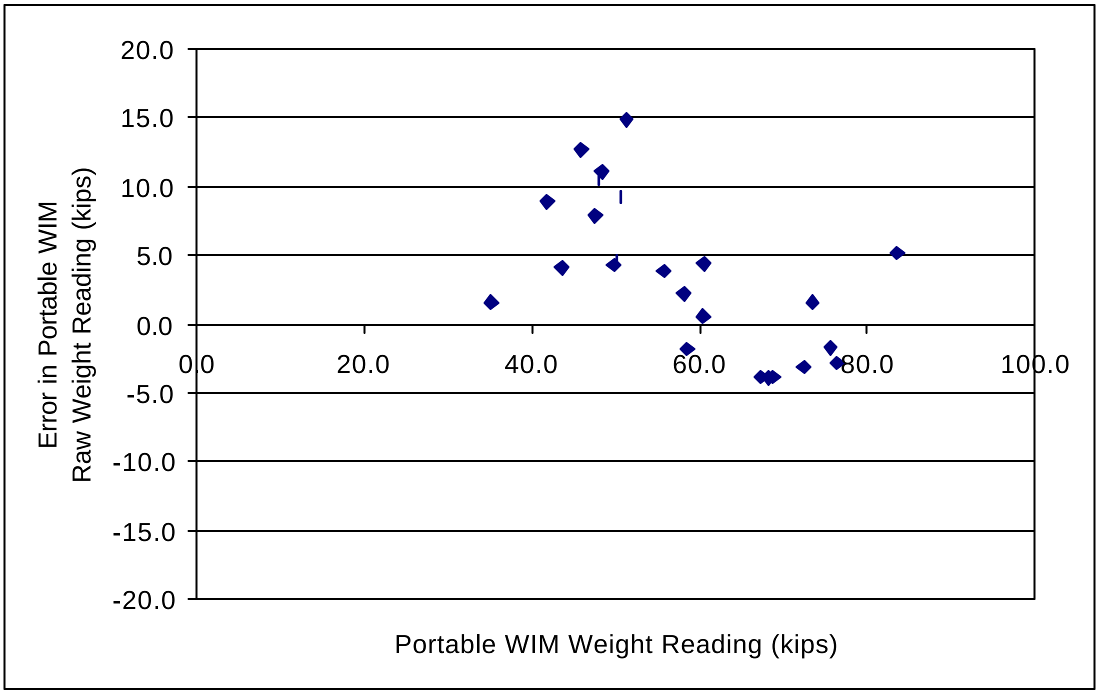


Figure A-6: Bias in Portable WIM Raw Weight Readings, Class 9 Trucks, 1/23/99

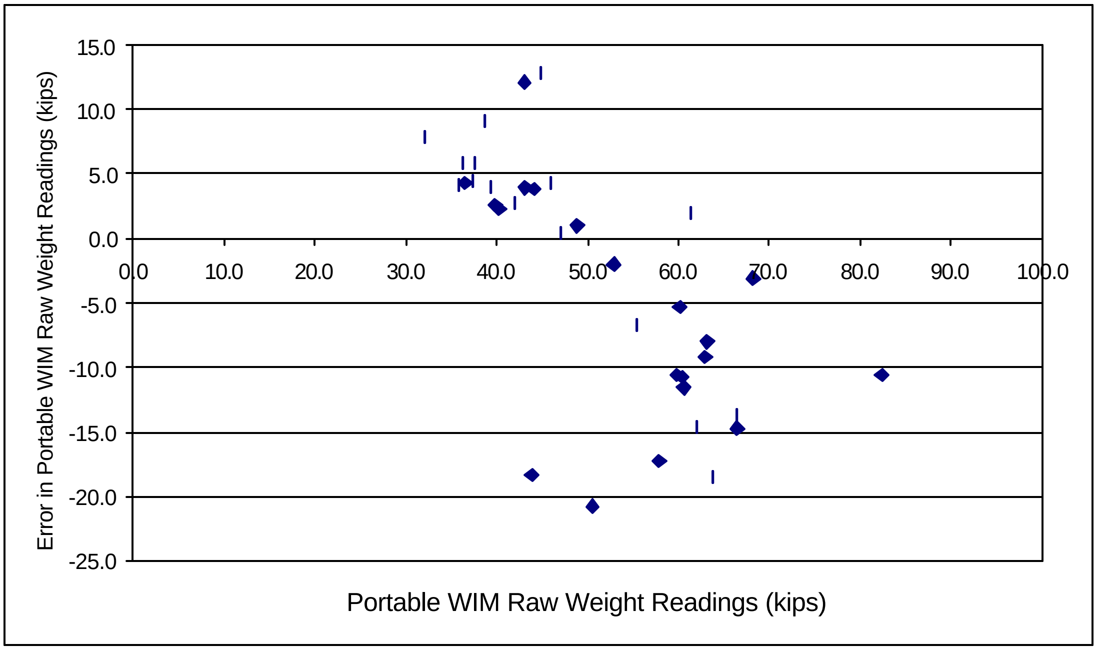


Figure A-7: Bias in Portable WIM Raw Weight Readings, Class 9 Trucks, 1/27/99

A.2 Accuracy of the MPS Method

The accuracy of the MPS method can be measured by comparing the MPS post-processed weights with the Douglas County weigh station weights. The bias of the MPS method will be measured relative to the MPS post-processed data. The MPS method is a feasible method of post-processing only if there is no bias in the error readings based on the MPS post-processed weight readings. In other words the error at low vehicle weights should be the same as the error at heavy vehicle weights for each of the truck classifications. In addition, bias will also be measured for the entire data set by ensuring that the average error of the MPS post-processed data is zero within a 95% confidence interval for each truck classification. This will guarantee that the MPS method does not overestimate or underestimate for entire vehicle classes.

Bias will also be measured between data collected on different days. For each of the three largest daily data sets for each of the four truck classes, statistical analysis will determine whether or not there is day-to-day variation in the total or absolute errors for each of the data sets. Finally, this analysis will develop error estimates based on the variance in the absolute error distributions. This error estimate should be reasonable relative to the gross vehicle weight for each truck classification. In addition, this error estimation will determine the minimum data set necessary to derive a statistically accurate weight distribution.

A.2.1 WIM Accuracy for Class 9-13 Trucks

A.2.1.1 MPS Error for Empty and Full Class 9-13 Trucks

The primary source of error in the portable WIM raw readings is the calibration error. The calibration error has the effect of overweighing light vehicles in a particular class and underweighing heavy vehicles in the same class. To ensure that the MPS method has accounted for this “compression” effect in the portable WIM, the error in the MPS method is measured across different values of the actual vehicle weight (as measured by the Douglas County WIM scale).

Figure A-8 graphs the error in the MPS readings versus the MPS reading for Class 9-13 trucks. The lack of any pattern in the data for figure A-8 indicate that there is no statistically significant bias in the MPS method relative to the MPS post-processed weight readings. Therefore, the WIM accuracy for empty Class 9-13 trucks is the same as the WIM accuracy for full Class 9-13 trucks.

Figure A-9 shows a statistical analysis performed for the MPS readings less than 40,000 pounds (representing empty trucks) and compared to the MPS readings more than 70,000 pounds (representing full trucks). The means of each of these two data sets were found not to be statistically different based on a 95% confidence interval. These results confirm that the WIM accuracy for empty and full Class 9-13 trucks can be considered as equal.

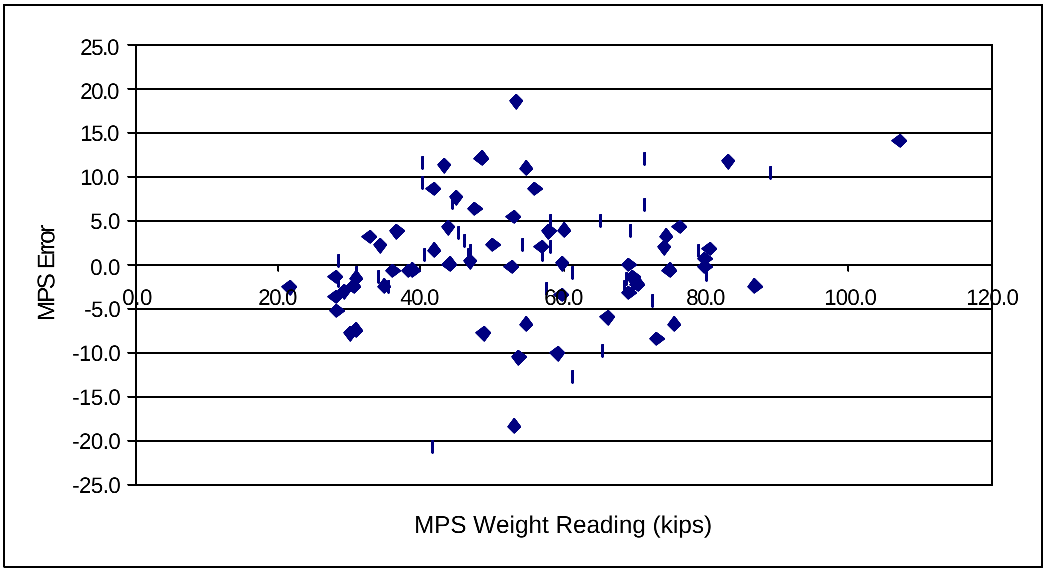


Figure A-8: Check for Bias in MPS Weight Data, Class 9-13 Trucks

	Descriptive Statistics of Errors from MPS Method for Class 9-13 Trucks	
	Trucks Less Than 40,000 lbs. kips	Trucks More Than 70,000 lbs.
Mean	-1.77	2.01
Upper Bounds Mean	-3.10	-0.92
Lower Bounds Mean	-0.45	4.94
Size of CI (95.0%)	1.33	2.93
Standard Error	0.64	1.40
Standard Deviation	2.91	6.26
Sample Variance	8.49	39.19
Count	21	20

Figure A-9: Descriptive Statistics for Empty and Full Class 9-13 Trucks

A.2.1.2 Total Error of MPS Method for Class 9-13 Trucks

The total error was analyzed to confirm that there is no bias in the MPS method for the entire Class 9-13 truck data set, such as systematically overestimating or underestimating the truck weight readings. Figure A-10 shows the distribution of the errors based on bins of 2 kips, while figure A-11 shows the descriptive statistics for the data set. The descriptive statistics indicate that the range of the mean contains the value zero with a 95% confidence interval. This indicates that there is no bias in the MPS method for Class 9-13 trucks. Figure A-13 shows the descriptive statistics for the three largest single day data sets for Class 9-13 trucks: January 23, January 27, and February 5. Similar to the entire data set, the descriptive statistics indicate that none of the means can be estimated as not equaling zero, and there is no skew in the normality of these distributions.

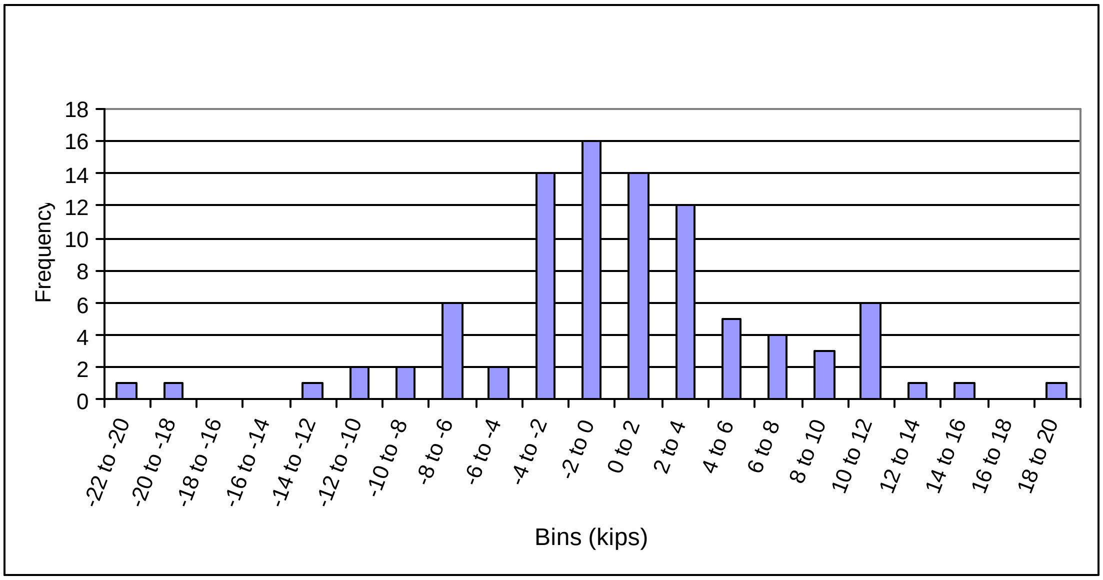


Figure A-10: Distribution of Error for MPS Method, Class 9-13 Trucks

	Descriptive Statistics for Error of MPS Method of All Class 9-13 Trucks
Mean	0.49
CI for Mean (95%)	1.36
Upper Bounds Mean	-0.87
Lower Bounds Mean	1.84
Median	0.96
Standard Error	0.68
Standard Deviation	6.55
Sample Variance	42.90
Count	92

Figure A-11: Descriptive Statistics For All Class 9-13 Trucks

	Descriptive Statistics for Error in MPS Method for Class 9-13 Trucks by Day		
	1/23/99	1/25/99	1/27/99
Mean	1.49	-5.10	-0.22
CI for Mean (95%)	2.07	8.23	2.39
Lower Bounds Mean	-0.59	-13.33	-2.61
Upper Bounds Mean	3.56	3.14	2.17
Standard Error	1.00	3.64	1.18
Median	1.31	-7.68	-0.90
Standard Deviation	4.91	11.51	7.06
Sample Variance	24.11	132.41	49.90
Count	24	10	36

Figure A-12: Descriptive Statistics For MPS Error For Class 9-13 Trucks by Day

A.2.1.3 Absolute Error of MPS Method for Class 9-13 Trucks

Figure A-13 shows descriptive statistics for the absolute value of the MPS errors for Class 9-13 trucks for the entire data set and for the three largest single day data sets. The value of the mean for the entire data set is 5.29. This results in reasonably small fractions of the gross vehicle weight values of Class 9-13 trucks (14.1% when empty and 7.1% when full). Therefore, only a very small data set needs to be created for Class 9-13 trucks to be considered a statistically accurate data set. Also based on these results, the final data analysis of Class 9-13 trucks will use bins the size of 5.0 kips. On average, each MPS post-processed weight reading will be misclassified by only one bin or less based on the 5.29 mean absolute MPS error. Virtually all data readings will be accurate to within two standard deviations of the mean which equates to all readings being less than 16.26 of the actual reading or a maximum of 3 bins error using 5 kip analysis bins.

The descriptive statistics also show that the means of the three daily data sets can be considered equal for 95% confidence intervals on the means. In addition, these means can not be considered statistically different than the mean of the overall data set for Class 9-13 trucks. This indicates that the MPS method can be applied to data on different days with the same absolute error for each daily set of Class 9-13 trucks.

	Descriptive Statistics of Absolute Error in MPS Method for Class 9-13 Trucks			
	Total	1/23/99	1/25/99	1/27/99
Mean	5.29	3.88	10.10	4.74
CI for Mean (95%)	1.16	1.38	4.95	1.75
Lower Bounds Mean	4.13	2.49	5.14	2.99
Upper Bounds Mean	6.45	5.26	15.05	6.49
Standard Error	0.59	0.67	2.19	0.86
Median	3.17	2.70	8.47	2.48
Standard Deviation	5.68	3.27	6.93	5.18
Sample Variance	32.25	10.72	47.97	26.84
Count	94	24	10	36

Figure A-13: Descriptive Statistics for Absolute Error in MPS Method for Class 9-13 Trucks

A.2.2 WIM Accuracy for Class 6-7 Trucks

A.2.2.1 MPS Error for Empty and Full Class 6-7 Trucks

The primary source of error in the portable WIM raw readings is the calibration error. The calibration error has the effect of overweighing light vehicles in a particular class and underweighing heavy vehicles in the same class. To ensure that the MPS method has accounted for this "compression" effect in the portable WIM, the error in the MPS method is measured across different values of the actual vehicle weight (as measured by the Douglas County WIM scale).

Figure A-14 shows the error in the MPS readings versus the MPS reading for Class 6-7 trucks. The lack of any pattern in the data for Figure A-15 indicate that there is no bias in the MPS method relative to the MPS post-processed weight readings. Figure A-15 shows the statistical analysis performed for the MPS readings less than 30,000 pounds and compared to the MPS readings more than 40,000 pounds. The means of each of these two sets of data were found not to be significantly different based on a 95%

confidence interval. Therefore, the error for full and empty Class 6-7 trucks can be considered to be equal. This result indicates that the MPS method has accounted for the affects of compression on the raw weight distribution for Class 6-7 trucks.

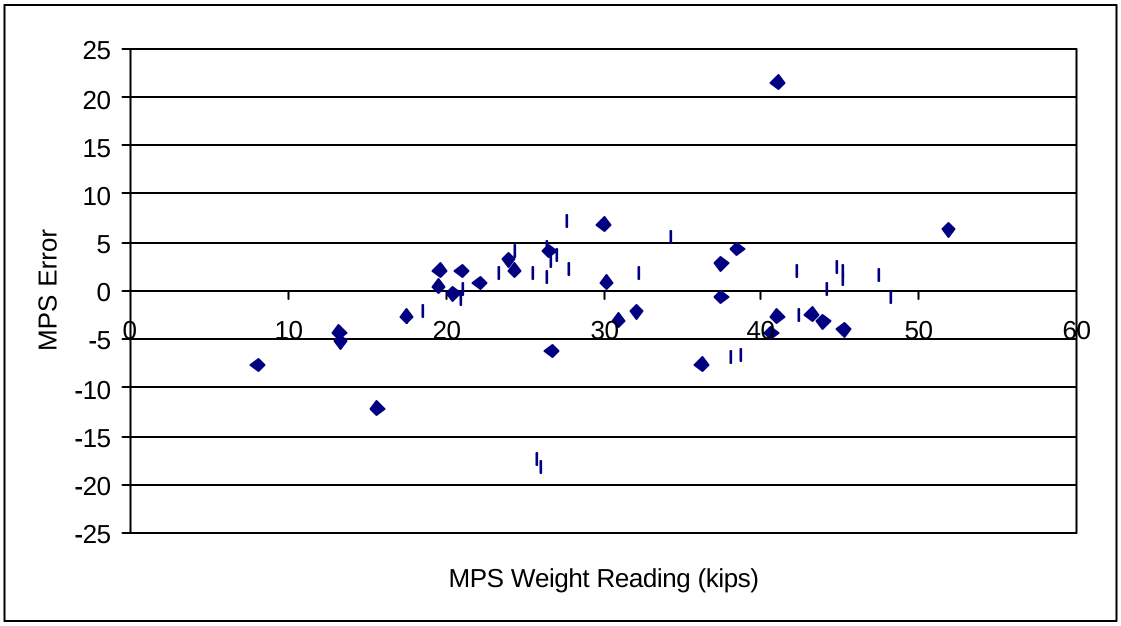


Figure A-14: Check for Compression in MPS Method for Class 6-7 Trucks

	Descriptive Statistics of Error for MPS Method for Class 6-7 Trucks	
	Trucks Less than 30,000 lbs.	Trucks More than 40,000 lbs.
Mean	-0.13	2.22
CI for Mean (95%)	2.51	3.18
Lower Bounds Mean	-2.64	-0.96
Upper Bounds Mean	2.37	5.39
Median	2.00	1.64
Standard Error	1.22	1.50
Standard Deviation	6.46	6.18
Sample Variance	41.74	38.23
Count	28	17

Figure A-15: Descriptive Statistics for Empty and Full Class 6-7 Trucks

A.2.2.2 Total Error of MPS Method for Class 6-7 Trucks

The total error was analyzed to confirm that there is no bias in the MPS method for the entire Class 6-7 truck data set such as systematically overestimating or underestimating the truck weight readings. Figure A-16 shows the distribution of the errors based on bins the size of 4 kips, while Figure A-17 shows the descriptive statistics for the data set. The descriptive statistics indicate that the mean can not be statistically proven to not be zero with a 95% confidence interval. This result indicates that there is no bias in the error measurement for Class 6-7 trucks.

Figure A-18 shows the descriptive statistics for the three largest single day data sets for Class 6-7 trucks: January 27, February 3, and February 8. Similar to the entire data set, the descriptive statistics indicate that none of the means can be estimated as not equaling zero. This indicates that there is no drift over time in the effectiveness of the MPS method for Class 6-7 trucks.

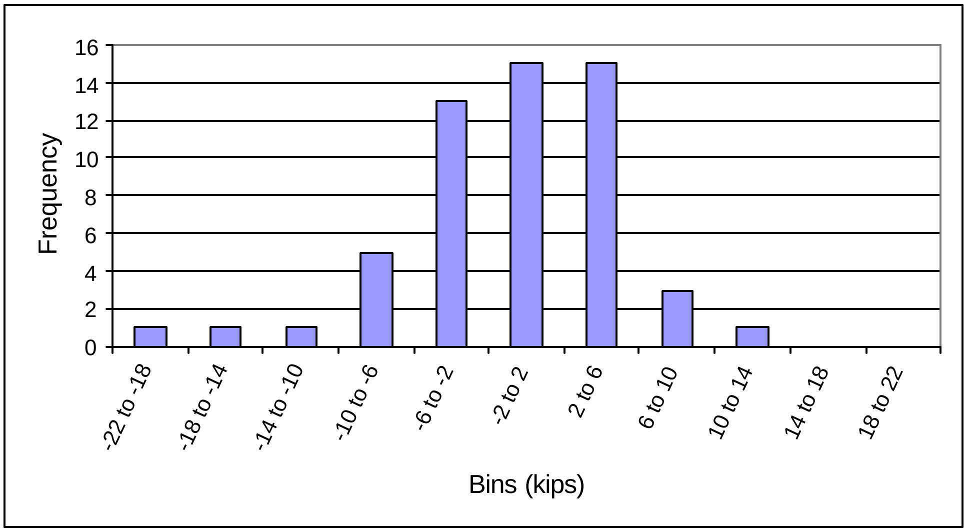


Figure A-16: Distribution of Errors from MPS Method for Class 6-7 Trucks

	Descriptive Statistics of Error in MPS Method for Class 6-7 Trucks
Mean	-0.37
CI for Mean (95%)	1.60
Lower Bounds Mean	-1.96
Upper Bounds Mean	1.23
Median	0.63
Standard Error	0.80
Standard Deviation	5.96
Sample Variance	35.54
Count	56

Figure A-17: Descriptive Statistics of Error in MPS Method for All Class 6-7 Trucks

	Descriptive Statistics of Error in MPS Method for Class 6-7 Trucks by Day		
	1/27/99	2/3/99	2/8/99
Mean	0.98	-0.80	-0.54
CI for Mean (95%)	3.48	2.58	3.10
Lower Bounds Mean	-2.49	-3.38	-3.64
Upper Bounds Mean	4.46	1.78	2.56
Median	1.66	-2.60	0.63
Standard Error	1.63	1.16	1.37
Standard Deviation	6.52	3.84	4.33
Sample Variance	42.54	14.76	18.76
Count	16	11	10

Figure A-18: Descriptive Statistics of Error in MPS Method for Class 6-7 Trucks by Day

A.2.2.3 Absolute Error of MPS Method for Class 6-7 Trucks

Figure A-19 shows descriptive statistics for the absolute value of the errors for the MPS method for Class 6-7 trucks for the entire data set and for the three largest single day data sets. The mean MPS error for the entire Class 6-7 data set is 4.12. On a percentage basis, this is equivalent to an average 13.7% MPS error for empty Class 6-7 trucks and an average 9.2% MPS error for full trucks.

Based on the error in the MPS method, the final data analysis of Class 6-7 trucks will use bins the size of 5.0 kips. On average, each MPS post-processed weight reading will be misclassified by only one bin or less based on the 4.12 mean absolute MPS error. Virtually all data readings will be accurate to within two standard deviations of the mean which equates to all readings being less than 12.7 of the actual reading or a maximum of 3 bins error using bin sizes of 5 kips for analysis.

The descriptive statistics also show that the confidence interval of the means for all three daily data sets overlap based on 95% confidence intervals. Therefore, there is no statistical drift over time in the accuracy of the MPS method for Class 6-7 trucks. The means for each of the daily data sets can not be considered statistically different from the mean of the overall data set for Class 6-7 trucks. This indicates that the MPS method can be applied to data on different days with the same absolute error for each daily set of Class 6-7 trucks.

	Descriptive Statistics of Absolute Errors in MPS Method for Class 6-7 Trucks			
	Total	1/27/99	2/3/99	2/8/99
Mean	4.12	4.19	3.30	2.44
CI for Mean (95%)	1.15	2.66	1.25	2.53
Lower Bounds Mean	2.98	1.54	2.05	-0.09
Upper Bounds Mean	5.27	6.85	4.55	4.97
Median	2.65	2.34	3.00	1.58
Standard Error	0.57	1.25	0.56	1.12
Standard Deviation	4.29	4.98	1.86	3.53
Sample Variance	18.37	24.83	3.46	12.47
Count	56	16	11	10

Figure A-19: Descriptive Statistics for Absolute MPS Error for Class 6-7 Trucks

A.2.3 WIM Accuracy for Class 8 Trucks

A.2.3.1 Error in the MPS Method for Empty and Loaded Class 8 Trucks

The primary source of error in the portable WIM raw readings is the calibration error. The calibration error has the effect of overweighing light vehicles in a particular class and underweighing heavy vehicles in the same class. To ensure that the MPS method has accounted for this “compression” effect in the portable WIM, the error in the MPS method is measured across different values of the actual vehicle weight (as measured by the Douglas County WIM scale).

Figure A-20 shows a scatterplot of the error in the MPS method for Class 8 trucks across gross vehicle weights. The lack of any pattern in the data for Figure A-20 indicates that the MPS method accounts for the compression effect in the raw weight readings. Figure A-21 shows the statistical analysis performed for the MPS readings less than 40,000 pounds (empty Class 8 trucks) and compared to the MPS readings more than 50,000 pounds (loaded Class 8 trucks). The means of each of these two sets of data were found not to be statistically different based on a 95% confidence interval. Therefore, the

Error from the MPS method does not vary between empty and loaded trucks. This result further bolsters the findings that the MPS method accounts for the compression error of the portable WIM equipment.

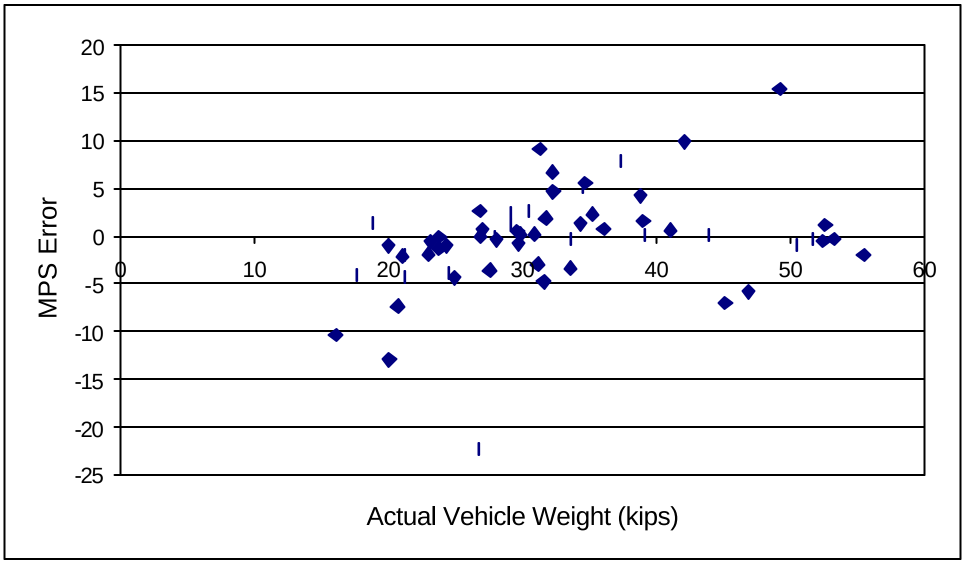


Figure A-20: Scatterplot of Error in MPS Method and Actual Weight, Class 8 Trucks

	Descriptive Statistics of Error from MPS Method for Class 8 Trucks	
	Trucks Less than 30,000 lbs.	Trucks More than 40,000 lbs.
Mean	-1.21	0.85
CI for Mean (95%)	1.56	3.91
Lower Bounds Mean	-2.78	-3.06
Upper Bounds Mean	0.35	4.77
Median	-0.82	-0.31
Standard Error	0.76	1.78
Standard Deviation	3.96	6.16
Sample Variance	15.64	37.89
Count	27	12

Figure A-21: Descriptive Statistics of Error from MPS Method for Empty and Loaded Class 8 Trucks

A.2.3.2 Total Error of the MPS Method for Class 8 Trucks

The total error was analyzed to confirm that there is no systematic overestimating or underestimating of vehicle weights based on the MPS method for Class 8 trucks. Figure A-22 shows the distribution of the errors from the MPS method for Class 8 trucks based on bins of 2 kips. The peak of the distribution occurs at the bin that contains an error of zero. Therefore, the graphic results indicate that the mean error is close to zero. The descriptive statistics for the error in MPS method for Class 8 trucks is shown in Figure A-23. The range for the confidence interval on the mean includes the value zero. Therefore, there is no statistical bias in the error for the MPS method that would result in systematic overweighing or underweighing of Class 8 trucks.

Figure A-24 shows the descriptive statistics for the three largest single day data sets for Class 8 trucks: January 23, January 27, and February 5. The confidence interval for the mean of each of the three individual errors includes zero. Therefore, there is no bias in the total error from the MPS method for any of the daily data sets or evidence of drift in the accuracy of the MPS method over time at a particular site.

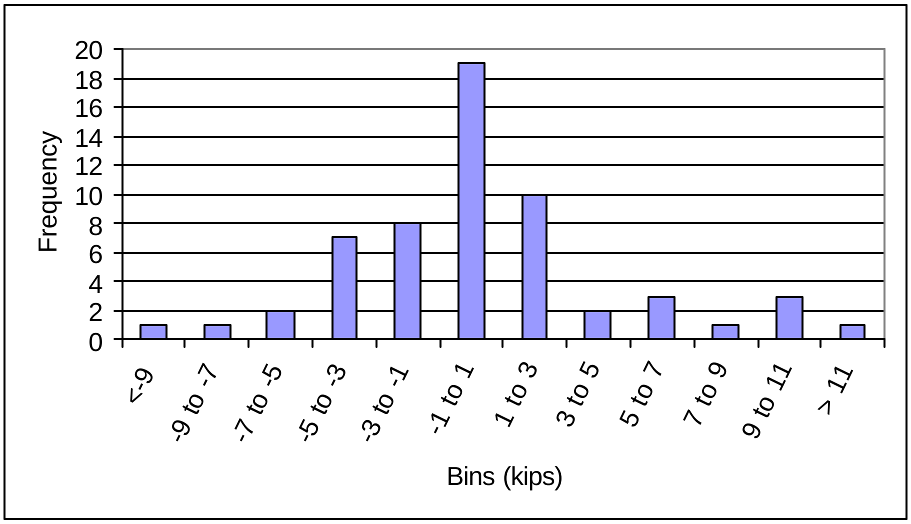


Figure A-22: Distribution of Errors in MPS Method for Class 8 Trucks

	Descriptive Statistics of Errors from MPS Method for all Class 8 Trucks
Mean	0.34
CI for Mean (95%)	1.21
Lower Bounds Mean	-0.87
Upper Bounds Mean	1.56
Median	-0.02
Standard Error	0.61
Standard Deviation	4.61
Sample Variance	21.27
Count	58

Figure A-23: Descriptive Statistics of Errors from MPS Method for All Class 8 Trucks

	Descriptive Statistics of Errors for MPS Method for Class 8 Trucks by Day		
	1/27/99	2/3/99	2/5/99
Mean	-0.05	1.22	-1.32
CI for Mean (95%)	1.18	3.19	2.33
Lower Bounds Mean	-1.23	-1.96	-3.64
Upper Bounds Mean	1.13	4.41	1.01
Median	-0.43	0.18	-1.41
Standard Error	0.54	1.49	1.08
Standard Deviation	1.95	5.76	4.03
Sample Variance	3.82	33.14	16.24
Count	13	15	14

Figure A-24: Descriptive Statistics of Errors for MPS Method for Class 8 Trucks by Day

A.2.3.3 Absolute Error of MPS Method for Class 8 Trucks

Figure A-25 shows descriptive statistics for the absolute value of the MPS errors for Class 8 trucks for the entire data set and for the three largest single day data sets. The value of the mean error from the MPS method is 3.11 for all Class 8 trucks. On a percentage basis, the absolute error for the MPS method for Class 8 trucks is 10.3% when empty (near 35,000 pounds) and 5.6% when fully loaded (near 60,000 pounds). Based on these results, the final data analysis of Class 8 trucks will use bins the size of 5 kips.

The descriptive statistics in Figure A-25 also show that the three daily confidence intervals of the means of the absolute errors for the MPS method overlap. Therefore, there is no statistically significant difference between the absolute error of the MPS method for Class 8 trucks on different days. This indicates that there is no drift in the absolute error over time. Therefore, the same absolute error value can be used for all daily sets of Class 8 trucks.

	Descriptive Statistics of Absolute Errors from MPS Method for Class 8 Trucks			
	Total	1/27/99	2/3/99	2/5/99
Mean	3.11	1.43	3.95	3.11
CI for Mean (95%)	0.89	0.87	2.35	1.60
Lower Bounds Mean	2.22	0.56	1.59	1.51
Upper Bounds Mean	4.01	2.29	6.30	4.71
Median	1.96	1.04	2.43	2.79
Standard Error	0.45	0.35	1.10	0.74
Standard Deviation	3.40	1.27	4.25	2.78
Sample Variance	11.54	1.61	18.05	7.70
Count	58	13	15	14

Figure A-25: Descriptive Statistics for Absolute MPS Error for Class 8 Trucks

A.2.4 WIM Accuracy for Class 5 Trucks

A.2.4.1 MPS Error for Light vs. Heavy Class 5 Trucks

The primary source of error in the raw portable WIM readings is the calibration error. The calibration error has the effect of overweighing light vehicles in a particular class and underweighing heavy vehicles in the same class. To ensure that the MPS method has accounted for this "compression" effect in the portable WIM readings, the error in the MPS method is measured across the full weight range of actual weights (as measured by the Douglas County weigh station) for Class 5 vehicles.

Figure A-26 shows the error in the MPS readings versus the actual value for Class 5 trucks. The lack of any pattern in the data for figure A-26 indicate that there is no bias in the MPS method relative to the actual weight of the vehicle. Figure A-27 shows the statistical analysis performed for the MPS readings less than 15,000 pounds and compared to the MPS readings more than 20,000 pounds. The means of each of these two sets of data were found not to be significantly different based on a 95% confidence interval. Therefore, there is no statistically significant difference between the errors in the MPS method for light Class 5 trucks and heavy Class 5 trucks. This result indicates that the MPS method has accounted for the affects of compression on the raw weight distribution for Class 5 trucks.

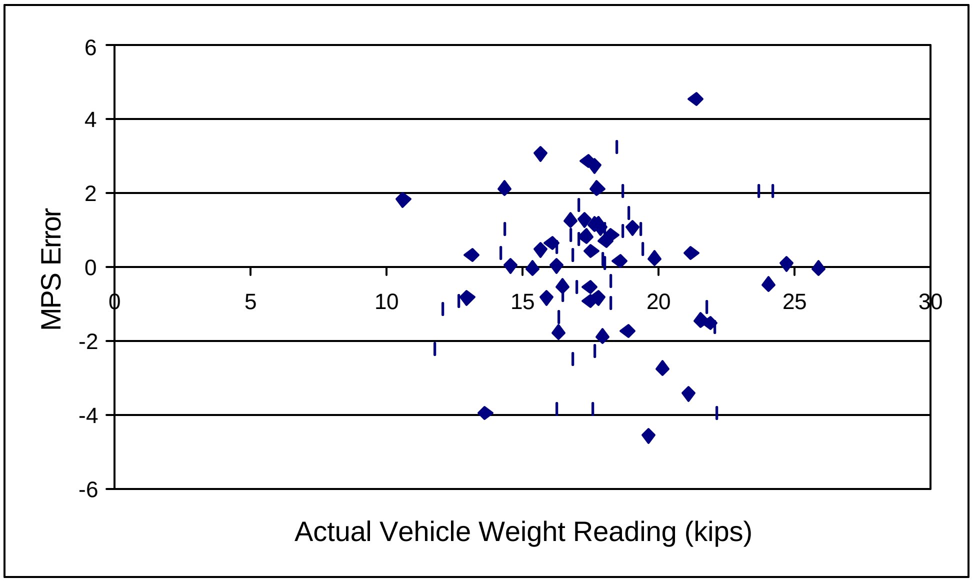


Figure A-26: Scatterplot of Error in MPS Method and Actual Vehicle Weight for Class 5 Trucks

	Descriptive Statistics of Errors in MPS Method for Class 5 Trucks	
	Trucks Less than 15,000 lbs.	Trucks More than 20,000 lbs.
Mean	-0.31	-0.51
CI for Mean (95.0%)	1.20	1.33
Lower Bounds Mean	-1.51	-1.85
Upper Bounds Mean	0.89	0.82
Median	0.03	-0.77
Standard Error	0.54	0.62
Standard Deviation	1.78	2.31
Sample Variance	3.18	5.33
Count	11	14

Figure A-27: Descriptive Statistics of Errors in MPS Method for Light and Heavy Class 5 Trucks

A.2.4.2 Total Error of MPS Method for Class 5 Trucks

The total error was analyzed to confirm that there is no bias in the MPS method for the entire Class 5 truck data set such as systematically overestimating or underestimating the truck weight readings. Figure A-28 shows the distribution of the errors based on bin sizes of 1 kip, while Figure A-29 shows the descriptive statistics for the data set. The descriptive statistics indicate that there is not a statistically significant difference between zero and the mean of the errors of the MPS method for Class 5 trucks based on a 95% confidence interval. This result indicates that the MPS method does not overweigh or underweigh the onroad Class 5 truck fleet.

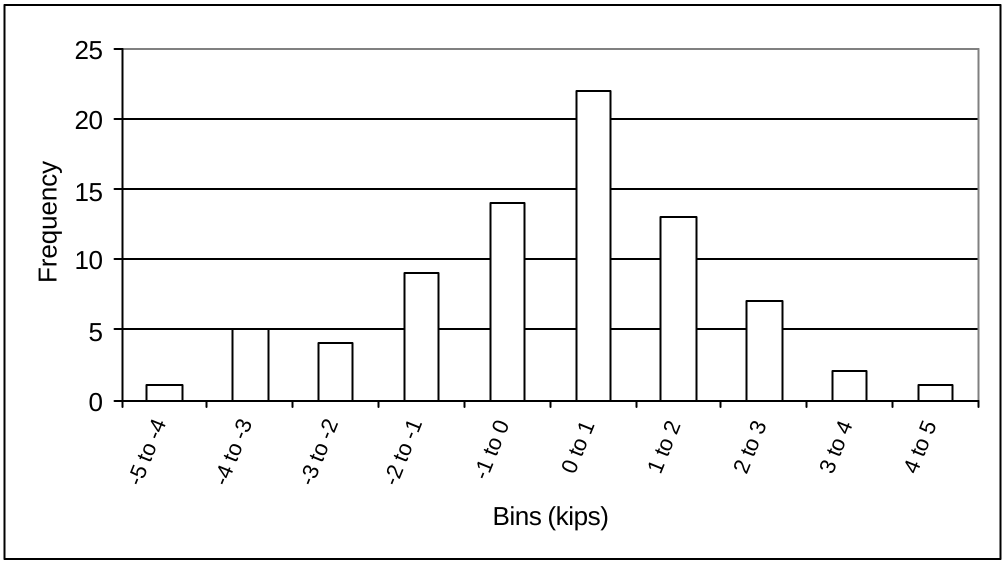


Figure A-28: Distribution of Errors of MPS Method for Class 5 Trucks

	Descriptive Statistics of Errors for MPS Method for All Class 5 Trucks
Mean	-0.03
CI for Mean (95%)	0.41
Lower Bounds Mean	-0.44
Upper Bounds Mean	0.38
Median	0.23
Standard Error	0.20
Standard Deviation	1.80
Sample Variance	3.26
Count	78

Figure A-29: Descriptive Statistics for All Class 5 Trucks

Figure A-30 shows the descriptive statistics for the three largest single day data sets for Class 5 trucks: January 23, January 27, and February 5. Similar to the entire data set, the descriptive statistics indicate that none of the means can be estimated as not equaling zero, and there is no skew in the normality of these distributions.

	Descriptive Statistics of Errors for MPS Method for Class 5 Trucks by Day		
Date	1/27/99	2/3/99	2/8/99
Mean	-0.57	-0.11	-0.01
CI for Mean (95.0%)	1.19	0.72	1.08
Lower Bounds Mean	-1.76	-0.83	-1.10
Upper Bounds Mean	0.61	0.61	1.07
Median	0.18	0.03	0.46
Standard Error	0.56	0.33	0.51
Standard Deviation	2.23	1.25	2.11
Sample Variance	4.96	1.56	4.45
Count	16	14	17

Figure A-30: Descriptive Statistics of Errors for MPS Method for Class 5 Trucks by Day

A.2.4.3 Absolute Error of MPS Method for Class 5 Trucks

Figure A-31 shows descriptive statistics for the absolute value of the errors for the MPS method for the entire data set and for the three largest single day data sets for Class 5 trucks. The mean MPS error for the entire data set is 1.39. On a percentage basis, this is equivalent to an average of 9.3% MPS error at 15,000 pound truck and 7.0% MPS error for a 20,000 pound truck.

Based on the error in the MPS method, the final data analysis of Class 5 trucks will use bins the size of 2.5 kips. On average, each MPS post-processed weight reading will be misclassified by only one bin or less based on the 1.39 mean absolute MPS error. Virtually all data readings will be accurate to within two standard deviations of the mean which equates to all readings being less than 3.67 of the actual reading or a maximum of 2 bins error using bin sizes of 2.5 kips.

The descriptive statistics also show that the range of the means for the MPS absolute error of all three daily data sets overlap based on 95% confidence intervals. Therefore, there is no statistical drift over time in the accuracy of the MPS method for Class 5 trucks. The means of the absolute error of the MPS method for each of the daily data sets can not be considered statistically different from the mean of the overall data set for Class 5 trucks. This indicates that the MPS method van be applied to data on different days with the same absolute error for each daily set of Class 5 trucks.

	Descriptive Statistics of Absolute Errors in MPS Method for Class 5 Trucks			
	Totals	1/27/99	2/3/99	2/8/99
Mean	1.39	1.79	0.89	1.69
CI for Mean (95%)	0.26	0.73	0.49	0.61
Lower Bounds Mean	1.14	1.06	0.40	1.08
Upper Bounds Mean	1.65	2.52	1.38	2.30
Median	1.05	1.45	0.60	1.64
Standard Error	0.13	0.34	0.23	0.29
Standard Deviation	1.14	1.37	0.85	1.19
Sample Variance	1.29	1.89	0.72	1.41
Count	78	16	14	17

Figure A-31: Descriptive Statistics for Absolute Errors in MPS Method for Class 5 Trucks

A.3 Conclusions on WIM Accuracy Using MPS Post-Processing Method

Application of the MPS post-processing method successfully accounted for the several sources of error in the raw portable WIM weight readings. Through comparisons of the raw portable WIM readings and the MPS post-processed readings, the MPS method was shown to be a statistically significant improvement in estimating the actual vehicle weight for all classes of vehicles. Specifically, there is no statistically significant difference in the error measurement for light or heavy trucks for any of the vehicle classes. Additionally, there is no statistical difference in the MPS error measurement between data collected on different days.

The average error using the MPS method was less than 15% for all truck classes. Based on the large quantity of data collected by the portable WIM, this level of average error will be capable of generating weight distributions for each classification. This 15% average error value is also used to establish the appropriate bin sizes for the final models. Class 5 trucks will be analyzed using 2,500 pound bin sizes. All other classes will use bin sizes of 5,000 pounds.

The MPS method was validated using a small range of temperatures due to the limited operating hours of the Douglas County weigh station. Ideally, the method would be tested under the full range of temperatures for which data was collected. Future portable WIM post-processing efforts should attempt to test during cold night time temperatures. However, the small range of temperatures included in this analysis revealed no difference between errors from the MPS method based on temperature.

APPENDIX B

List of Contingency Tables and Chi-Square Values

The following tables were developed for the analysis performed in the chapter describing the final data and models (Chapter 8). Contingency tables are shown with observed frequencies without parentheses and expected frequencies inside of parentheses. Contingency tables comparing horsepower to other variables are exclusively for Class 9-13 trucks. All tables featuring chi-square comparisons are made at the 5% significance level for horsepower comparisons and the 1% significance level for weight comparisons.

	Truck Weight Ranges				
Horsepower Range	Less than 40,000 pounds	40,000-55,000 pounds	55,000-69,999 pounds	70,000 pounds and over	Totals
<350	10 (6.1)	6 (5.6)	8 (5.5)	41 (47.8)	65
350-399	13 (11.8)	13 (10.9)	10 (10.6)	90 (92.7)	126
400-449	10 (14.7)	16 (13.6)	8 (13.2)	123 (115.5)	157
450 and over	8 (8.5)	3 (7.9)	11 (7.7)	69 (67.0)	91
Totals	41	38	37	323	439

Figure B-1, Contingency Table for Horsepower and Truck Weight Ranges

	Truckstop Survey Locations							
Horsepower Range	10-4	Petro *(1)*	Pilot	TA	TA-Jax	Pit Stop	Petro *(2)*	Totals
Less than 399	7 (6.4)	8 (10.2)	8 (5.7)	6 (4.5)	4 (4.8)	7 (5.4)	4 (7.0)	43
400-449	10 (7.7)	18 (12.3)	6 (6.9)	4 (5.4)	5 (5.8)	4 (6.5)	6 (8.4)	53
450 and over	3 (5.9)	6 (9.5)	4 (5.3)	4 (4.2)	6 (4.5)	6 (5.1)	12 (6.5)	41
Totals	20	32	18	14	15	17	22	137

Figure B-2, Contingency Table for Horsepower and Truckstop Locations

	Truck Survey Locations					
Horsepower Ranges	Douglas Station	Franklin Station	Monroe Station	Troup Station	Combined Truckstops	Totals
Less than 350	27 (24.0)	12 (6.7)	9 (6.8)	6 (7.1)	11 (20.4)	65
350-399	62 (46.5)	8 (12.9)	11 (13.2)	12 (13.8)	33 (39.6)	126
400-449	49 (57.9)	17 (16.1)	18 (16.5)	20 (17.2)	53 (49.4)	158
450 and over	24 (33.6)	8 (9.3)	8 (9.5)	10 (9.9)	41 (25.6)	91
Totals	162	45	46	48	138	453

Figure B-3, Contingency Table for Horsepower and Weigh Stations/Combined Truckstops

	Survey Locations					
Horsepower Ranges	Douglas Station (1999)	Franklin Station	Monroe Station	Troup Station	Combined Truckstops	Totals
Less than 350	6 (9.0)	12 (5.7)	9 (5.8)	6 (6.1)	11 (17.4)	44
350-399	22 (17.5)	8 (11.1)	11 (11.4)	12 (11.9)	33 (34.1)	86
400-449	24 (26.9)	17 (17.1)	18 (17.4)	20 (18.2)	53 (52.3)	132
450 and over	19 (17.5)	8 (11.1)	8 (11.4)	10 (11.9)	41 (34.1)	86
Totals	71	45	46	48	138	362

Figure B-4, Contingency Table for Horsepower and Data Collected in 1998 to1999

	Trip Types				
Horsepower Ranges	II Trips	IX Trips	XI Trips	XX Trips	Totals
Less than 350	2 (1.8)	7 (3.9)	13 (13.5)	11 (13.8)	33
350-399	3 (2.4)	3 (5.2)	24 (18.0)	14 (18.4)	44
400-449	2 (2.6)	5 (5.6)	14 (19.2)	26 (19.6)	47
450 and over	0 (0.2)	0 (0.4)	1 (1.2)	2 (1.3)	3
Totals	7	15	52	53	127

Figure B-5, Contingency Table for Horsepower and Different Trip Types for pre-1996 Model Year Trucks

	Trip Types				
Horsepower Ranges	II Trips	IX Trips	XI Trips	XX Trips	Totals
Less than 350	0 (0.2)	0 (0.9)	4 (2.5)	4 (4.4)	8
350-399	2 (0.5)	2 (2.1)	10 (5.9)	5 (10.5)	19
400-449	0 (0.7)	3 (3.2)	7 (8.8)	18 (15.4)	25
450 and over	0 (0.6)	4 (2.8)	4 (7.8)	17 (13.8)	25
Totals	2	9	25	44	80

Figure B-6, Contingency Table for Horsepower and Trip Types for 1996 and Newer Model Year Trucks

	Truck Company Types		
Horsepower Ranges	For-Hire	Private	Totals
Less than 350	22 (24.6)	6 (3.4)	28
350-399	26 (28.1)	6 (3.9)	32
400-449	50 (48.3)	5 (6.7)	55
450 and over	25 (22.0)	0 (3.0)	25
	123	17	140

Figure B-7, Contingency Table for Horsepower and Truck Company Types

	Truck Body Types		
Horsepower Ranges	Container Trucks	Flatbed Trucks	Totals
Less than 350	25 (23.3)	3 (4.7)	28
350-399	24 (21.7)	2 (4.3)	26
400-449	41 (40.8)	8 (8.2)	49
450 and over	15 (19.2)	8 (3.8)	23
Totals	105	21	126

Figure B-8, Contingency Table for Horsepower and Truck Body Types

	Weight Ranges (000s pounds)								
	< 40	40-45	45-50	50-55	55-60	60-65	65-70	> 70	Totals
Mon.	1055 (939)	213 (200)	165 (177)	142 (175)	160 (170)	154 (169)	210 (236)	723 (758)	2823
Tues.	1426 (1457)	278 (311)	277 (274)	274 (271)	264 (263)	259 (263)	368 (367)	1235 (1177)	4383
Wed.	797 (784)	198 (167)	141 (147)	139 (146)	136 (142)	143 (141)	204 (197)	596 (633)	2357
Thur.	1480 (1494)	323 (319)	288 (281)	277 (278)	271 (270)	264 (270)	409 (376)	1177 (1206)	4493
Fri.	1808 (1692)	371 (361)	313 (318)	314 (315)	298 (306)	278 (305)	368 (426)	1333 (1367)	5088
Sat.	458 (502)	92 (107)	114 (94)	106 (93)	97 (91)	106 (91)	128 (126)	408 (406)	1510
Sun.	464 (625)	121 (133)	109 (118)	140 (116)	126 (113)	146 (113)	195 (157)	573 (505)	1881
Totals	7483	1596	1407	1392	1352	1350	1882	6045	22507

Figure B-9, Contingency Table for Day of Week and Truck Weight Bins, Midday Time Period, Class 9 Trucks

	Weight Ranges (000s pounds)								
	< 40	40-45	45-50	50-55	55-60	60-65	65-70	> 70	Totals
Mon.	14.4	0.8	0.7	6.1	0.5	1.4	2.9	1.6	28.5
Tues.	0.7	3.5	0.0	0.0	0.0	0.1	0.0	2.8	7.1
Wed.	0.2	5.7	0.3	0.3	0.2	0.0	0.2	2.2	9.2
Thur.	0.1	0.1	0.2	0.0	0.0	0.1	3.0	0.7	4.2
Fri.	8.0	0.3	0.1	0.0	0.2	2.4	7.8	0.8	19.6
Sat.	4.8	2.1	4.1	1.7	0.4	2.6	0.0	0.0	15.8
Sun.	41.6	1.1	0.6	4.8	1.5	9.8	9.0	9.1	77.6
Totals	69.9	13.6	6.0	13.0	2.9	16.4	22.9	17.3	162.0

Figure B-10, Chi-Square Values for Day of Week and Truck Weight Bins, Midday Time Period Class 9 Trucks

	Weight Ranges (000s pounds)								
	< 40	40-45	45-50	50-55	55-60	60-65	65-70	> 70	Totals
Mon.	7.6	0.4	0.5	4.3	0.3	0.4	1.8	0.8	16.1
Tues.	4.1	4.8	0.1	0.5	0.1	0.2	0.3	4.8	14.9
Wed.	0.2	4.5	0.2	0.0	0.1	0.4	0.7	1.3	7.3
Thur.	2.5	0.0	0.4	0.2	0.1	0.1	5.0	0.1	8.5
Fri.	2.2	0.0	0.0	0.3	0.0	0.7	5.3	0.1	8.6
Totals	16.6	9.7	1.2	5.4	0.6	1.9	13.08	7.1	55.5

Figure B-11, Chi-Square Values for Monday-Friday and Truck Weight Bins, Midday Time Period Class 9 Trucks

	Weight Ranges (000s pounds)								
	< 40	40-45	45-50	50-55	55-60	60-65	65-70	> 70	Totals
Tuesdays	2.1	4.2	0.0	0.1	0.0	0.1	0.1	4.0	10.6
Wednesdays	0.0	4.9	0.3	0.3	0.1	0.3	0.4	1.6	7.9
Thursdays	1.0	0.0	0.2	0.0	0.1	0.1	3.7	0.3	5.3
Fridays	4.6	0.1	0.1	0.0	0.1	0.9	6.7	0.3	12.7
Totals	7.6	9.3	0.6	0.3	0.3	1.4	10.9	6.2	36.5

Figure B-12, Chi-Square Values for Tuesday-Friday and Truck Weight Bins, Midday Time Period Class 9 Trucks

	Weight Ranges (000s pounds)													
	< 30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	70-75	75-80	80-85	85-90	> 90	Totals
Saturdays	7.6	1.3	0.9	0.0	3.3	0.0	0.0	0.1	0.9	0.0	1.0	0.1	0.1	0.0	15.2
Sundays	5.7	1.0	0.7	0.0	2.5	0.0	0.0	0.0	0.7	0.0	0.8	0.0	0.1	0.0	11.5
Totals	13.3	2.3	1.5	0.0	5.9	0.0	0.0	0.1	1.6	0.0	1.8	0.1	0.2	0.0	26.7

Figure B-13, Chi-Square Values for Saturday and Sunday by Truck Weight Bins, Midday Time Period Class 9 Trucks

	Weight Ranges (000s of pounds)														
Day of Week	< 30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	70-75	75-80	80-85	85-90	> 90	Totals
Mon.	0.3	1.7	6.5	7.6	0.1	0.5	3.2	7.4	10.5	2.9	2.5	4.4	0.0	0.0	47.5
Tues.	20.1	12.5	0.5	0.5	0.2	2.5	4.9	1.3	0.1	3.0	2.5	0.5	1.0	0.4	49.9
Wed.	4.1	12.7	4.0	0.0	1.8	4.5	3.5	2.6	2.8	0.8	1.4	1.4	6.2	13.8	59.7
Thur.	0.3	0.4	0.1	0.0	1.9	0.6	6.9	9.1	1.6	0.0	4.5	8.3	5.3	3.1	42.0
Fri.	3.1	1.1	0.0	1.0	1.3	0.3	0.6	0.3	0.8	1.6	3.7	3.8	4.1	17.3	39.0
Sat.	6.4	4.6	6.9	5.3	0.8	0.3	1.2	0.4	4.5	4.0	5.9	4.2	2.9	3.5	50.8
Sun.	2.4	2.0	5.2	4.1	1.2	0.3	2.3	2.9	0.4	0.6	3.2	0.4	0.4	0.1	25.5
Totals	36.6	34.9	23.2	18.5	7.3	8.9	22.6	24.0	20.9	12.9	23.7	23.0	19.9	38.1	314.5

Figure B-14, Chi-Square Values by Day of Week and Truck Weight Bins, Afternoon Time Period, Class 9 Trucks

	Weight Ranges (000s of pounds)			
Day of Week	< 40	40-65	> 65	Totals
Mondays	0.0	0.9	0.8	1.6
Tuesdays	1.3	0.3	0.3	1.9
Wednesdays	0.9	1.5	0.1	2.5
Thursdays	0.1	0.2	0.4	0.7
Fridays	5.2	0.3	6.5	12.0
Saturdays	0.0	0.8	1.1	1.9
Sundays	28.4	0.2	19.2	47.8
Totals	35.9	4.2	28.4	68.4

Figure B-15, Chi-Square Values by Day of Week and Reduced Truck Weight Bins, Afternoon Time Period, Class 9 Trucks

	Weight Ranges (000s of pounds)			
Day of Week	< 40	40-65	> 65	Totals
Mondays	0.4	1.0	0.1	1.5
Tuesdays	0.0	0.2	0.1	0.3
Wednesdays	0.0	1.4	0.9	2.3
Thursdays	1.1	0.2	1.8	3.1
Fridays	2.0	0.4	3.5	5.8
Saturdays	0.1	0.9	0.4	1.4
Totals	3.7	4.0	6.8	14.4

Figure B-16, Chi-Square Values for Monday-Saturday by Reduced Truck Weight Bins, Afternoon Time Period, Class 9 Trucks

	Weight Bins (000s of pounds)													
	< 30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	70-75	75-80	80-85	85-90	> 90	TOT
Mon.	0.3	1.7	6.5	7.6	0.1	0.5	3.2	7.4	10.5	2.9	2.5	4.4	0.0	0.0	47.53
Tues.	20.1	12.5	0.5	0.5	0.2	2.5	4.9	1.3	0.1	3.0	2.5	0.5	1.0	0.4	49.98
Wed.	4.1	12.7	4.0	0.0	1.8	4.5	3.5	2.6	2.8	0.8	1.4	1.4	6.2	13.8	59.7
Thurs.	0.3	0.4	0.1	0.0	1.9	0.6	6.9	9.1	1.6	0.0	4.5	8.3	5.3	3.1	42.03
Fri.	3.1	1.1	0.0	1.0	1.3	0.3	0.6	0.3	0.8	1.6	3.7	3.8	4.1	17.3	38.99
Sat.	6.4	4.6	6.9	5.3	0.8	0.3	1.2	0.4	4.5	4.0	5.9	4.2	2.9	3.5	50.8
Sun.	2.4	2.0	5.2	4.1	1.2	0.3	2.3	2.9	0.4	0.6	3.2	0.4	0.4	0.1	25.5
Totals	36.6	34.9	23.2	18.5	7.3	8.9	22.6	24.0	20.9	12.9	23.7	23.0	19.9	38.1	314.5

Figure B-17, Chi-Square Values by Day of Week and Truck Weight Bins, Night Time Period, Class 9 Trucks

	Weight Bins (000s of pounds)			
Location	< 40	40-65	> 65	Totals
I20-DgPWIM	32.5	2.5	7.4	42.4
I75-Clay	36.2	4.0	6.6	46.8
I75-Cobb	27.6	17.5	0.0	45.1
I85-Arpt	13.6	3.4	18.6	35.5
Totals	109.9	27.4	32.6	169.8

Figure B-18, Chi-Square Values by Location and Truck Weight Bins, Night Time Period, Class 9 Trucks

	Weight Bins (000s of pounds)			
Location	< 40	40-65	> 65	Totals
I20-Douglas Co.	3483 (3536)	2864 (2781)	3148 (9495)	9495
I75-Clayton Co.	723 (695)	508 (547)	636 (625)	1867
I75-Cobb Co.	1024 (992)	733 (780)	906 (891)	2663
I85-Airport	554 (554)	461 (435)	473 (498)	1488
I75-Howell Mill Rd.	439 (445)	328 (350)	428 (400)	1195
Totals	6223	4894	5591	16708

Figure B-19, Expected and Observed (in parentheses) Frequencies by Location and Truck Weight Bins, Midday Time Period, Tuesday-Friday, Class 9 Trucks

	Weight Bins (000s of pounds)			
Location	< 40	40-65	> 65	Totals
I20-Douglas Co.	386 (409)	327 (306)	359 (357)	1072
I75-Clayton Co.	118 (133)	95 (100)	136 (116)	349
I75-Cobb Co.	495 (471)	337 (352)	401 (411)	1233
I75-Howell Mill Rd.	116 (102)	75 (76)	77 (89)	268
Totals	1115	834	973	2922

Figure B-20, Contingency Table for Location and Truck Weight Bins, Midday Time Period, Monday, Class 9 Trucks

	Weight Bins (000s of pounds)			
Location	< 40	40-65	> 65	Totals
I20-Douglas Co.	521 (559)	734 (724)	835 (807)	2090
I75-Clayton Co.	101 (94)	123 (122)	127 (136)	351
I75-Cobb Co.	158 (154)	207 (200)	211 (222)	576
I85-Airport	72 (56)	66 (72)	70 (80)	208
I75-Howell Mill Rd.	52 (41)	40 (53)	61 (59)	153
Totals	904	1170	1304	3378

Figure B-21, Contingency Table for Location and Truck Weight Bins, Midday Time Period, Weekends, Class 9 Trucks

	Weight Bins (000s of pounds)			
Location	< 40	40-65	> 65	Totals
I20-Douglas Co.	2474 (2556)	2598 (2547)	2962 (2932)	8034
I75-Clayton Co.	393 (357)	334 (356)	395 (409)	1122
I75-Cobb Co.	496 (467)	454 (465)	518 (536)	1468
I85-Airport	167 (164)	148 (164)	201 (188)	516
I75-Howell Mill Rd.	766 (752)	747 (750)	852 (863)	2365
Totals	4296	4281	4928	13505

Figure B-22, Contingency Table for Location and Truck Weight Bins, Afternoon Time Period, Monday-Saturday, Class 9 Trucks

	Weight Bins (000s of pounds)			
Location	< 40	40-65	> 65	Totals
I20-Douglas Co.	301 (317)	474 (458)	597 (597)	1372
I75-Clayton Co.	34 (21)	24 (30)	32 (39)	90
I75-Cobb Co.	66 (64)	84 (92)	125 (120)	275
I75-Howell Mill Rd.	9 (9)	11 (13)	18 (17)	38
Totals	410	593	772	1775

Figure B-23, Contingency Table for Location and Truck Weight Bins, Afternoon Time Period, Sunday, Class 9 Trucks

Time Periods		Weight Ranges (000s of Pounds)			
Time of Day	Day of Week	< 40	40-65	> 65	TOT
9:00AM – 3:00PM	Mondays	11 (14.6)	29 (30.3)	39 (34.1)	79
9:00AM – 3:00PM	Tuesdays	11 (10.0)	24 (20.7)	19 (23.3)	54
9:00AM – 3:00PM	Wednesdays	28 (39.1)	78 (81.4)	106 (91.4)	212
9:00AM – 3:00PM	Thursdays	12 (9.8)	19 (20.4)	22 (22.9)	53
9:00AM – 3:00PM	Fridays	26 (23.8)	51 (49.5)	52 (55.6)	129
9:00AM – 3:00PM	Sat., Sun.	19 (12.4)	23 (25.7)	25 (28.9)	67
3:00PM – 7:00PM	Mondays	22 (24.7)	57 (51.5)	55 (57.8)	134
3:00PM – 7:00PM	Tuesdays	9 (5.9)	12 (12.3)	11 (13.8)	32
3:00PM – 7:00PM	Wednesdays	19 (12.4)	24 (25.7)	24 (28.9)	67
3:00PM – 7:00PM	Thursdays	12 (10.2)	19 (21.1)	24 (23.7)	55
3:00PM – 7:00PM	Fridays	24 (36.9)	82 (76.8)	94 (86.3)	200
3:00PM – 7:00PM	Sat., Sun.	18 (11.3)	21 (23.4)	22 (26.3)	61
	Totals	211	439	493	1143

Figure B-24, Contingency Table for Time Periods and Weight Ranges, 9:00AM-7:00PM, Class 10-13 Trucks

Time Periods		Weight Ranges (000s of pounds)			
Time of Day	Day of Week	< 40	40-65	> 65	Totals
7:00PM – 9:00AM	Tuesdays	18 (23.3)	85 (72.7)	33 (40.0)	136
7:00PM – 9:00AM	Wednesdays	60 (50.2)	138 (156.6)	95 (86.3)	293
7:00PM – 9:00AM	Thursdays	29 (36.1)	119 (112.7)	63 (62.1)	211
7:00PM – 9:00AM	Fridays	62 (65.1)	212 (203.0)	106 (111.9)	380
7:00PM – 9:00AM	Saturdays	47 (49.8)	159 (155.5)	85 (85.7)	291
7:00PM – 9:00AM	Sundays	26 (17.5)	42 (54.5)	34 (30.0)	102
	Totals	242	755	416	1413

Figure B-25, Contingency Table for Time Periods and Weight Ranges, 7:00PM-9:00AM, Class 10-13 Trucks

Location and Time Periods			Weight Ranges (000s of pounds)			
Location	Time of Day	Day of Week	< 40	40-65	65+	Totals
I-20 Douglas County	9:00AM – 7:00PM	Mondays – Sundays	113 (129.6)	311 (310.7)	359 (342.7)	783
I-75 Clayton County	9:00AM – 7:00PM	Mondays – Sundays	46 (38.6)	91 (92.5)	96 (102.0)	233
I-85 S. of Airport	9:00AM – 7:00PM	Mondays – Sundays	43 (34.8)	81 (83.3)	86 (91.9)	210
I-75 Howell Mill Rd.	9:00AM – 7:00PM	Mondays – Sundays	9 (8.1)	23 (19.4)	17 (21.4)	49
		Totals	211	506	558	1275

Figure B-26, Contingency Table for Location and Weight Ranges, 9:00AM-7:00PM, Class 10-13 Trucks

Location and Time Periods			Weight Ranges (000s of pounds)			
Location	Time of Day	Day of Week	40	40-65	65+	Totals
I-20 Douglas County	7:00PM – 9:00AM	Tuesdays – Sundays	103 (126.4)	398 (394.3)	237 (217.3)	738
I-75 Clayton County	7:00PM – 9:00AM	Tuesdays – Sundays	49 (39.0)	114 (121.8)	65 (67.1)	228
I-85 S. of Airport	7:00PM – 9:00AM	Tuesdays – Sundays	13 (12.0)	42 (37.4)	15 (20.6)	70
I-75 Howell Mill Rd.	7:00PM – 9:00AM	Tuesdays – Sundays	77 (64.6)	201 (201.4)	99 (111.0)	377
		Totals	242	755	416	1413

Figure B-27, Contingency Table for Location and Weight Ranges, 7:00PM-9:00AM, Tuesdays-Sundays, Class 10-13 Trucks

Location and Time Periods			Weight Ranges (000s of pounds)		
Location	Time of Day	Day of Week	< 40	> 40	TOT
I-20 Douglas County	7:00PM – 9:00AM	Mondays	15 (36.3)	107 (85.7)	122
I-75 Clayton County	7:00PM – 9:00AM	Mondays	33 (12.8)	10 (30.2)	43
I-85 S. of Airport	7:00PM – 9:00AM	Mondays	5 (3.9)	8 (9.1)	13
		Totals	53	125	178

Figure B-28, Contingency Table for Location and Weight Ranges, 7:00PM-9:00AM, Mondays, Class 10-13 Trucks

Time Periods		Weight Ranges (000s of pounds)			
Time of Day	Day of Week	< 30	30-40	> 40	Totals
7:00PM – 9:00AM	Tuesdays	19 (25.0)	12 (9.1)	10 (7.0)	41
7:00PM – 9:00AM	Wednesdays	221 (214.9)	81 (78.0)	51 (60.2)	353
7:00PM – 9:00AM	Thursdays	58 (63.3)	24 (23.0)	22 (17.7)	104
7:00PM – 9:00AM	Fridays	108 (112.0)	34 (40.6)	42 (31.4)	184
7:00PM – 9:00AM	Saturdays	137 (127.0)	46 (46.4)	27 (35.8)	210
	Totals	543	197	152	892

Figure B-29, Contingency Table for Day of Week and Weight Ranges, All Locations, 7:00PM-9:00AM, Tuesdays-Saturdays, Class 6-7 Trucks

Time Periods		Weight Ranges (000s of pounds)			
Time of Day	Day of Week	< 30	30-40	> 40	Totals
3:00PM – 7:00PM	Mondays	71 (72.1)	16 (25.6)	46 (35.3)	133
3:00PM – 7:00PM	Tuesdays	98 (96.5)	38 (34.3)	42 (47.2)	178
3:00PM – 7:00PM	Wednesdays	131 (123.6)	48 (43.9)	49 (60.5)	228
3:00PM – 7:00PM	Thursdays	120 (131.2)	48 (46.6)	74 (64.2)	242
3:00PM – 7:00PM	Fridays	150 (138.7)	52 (49.3)	54 (67.9)	256
3:00PM – 7:00PM	Saturdays	52 (56.9)	19 (20.2)	34 (27.9)	105
3:00PM – 7:00PM	Sundays	11 (14.1)	4 (5.0)	11 (6.9)	26
	Totals	633	225	310	1168

Figure B-30, Contingency Table for Day of Week and Weight Ranges, All Locations, 3:00PM - 7:00PM, Mondays-Sundays, Class 6-7 Trucks

Time Periods		Weight Ranges (000s of pounds)			
Time of Day	Day of Week	< 30	30-40	> 40	Totals
9:00AM – 3:00PM	Mondays	115	41	79	235
9:00AM – 3:00PM	Tuesdays	31	8	20	59
9:00AM – 3:00PM	Fridays	103	33	32	168
	Totals	249	82	131	462

Figure B-31, Contingency Table for Day of Week and Weight Ranges, All Locations, 9:00AM-3:00PM, Mondays, Tuesdays, and Fridays, Class 6-7 Trucks

Time Periods		Weight Ranges (000s of pounds)			
Time of Day	Day of Week	< 30	30-40	> 40	Totals
9:00AM – 3:00PM	Wednesdays	103 (102.5)	33 (39.2)	32 (26.3)	168
9:00AM – 3:00PM	Thursdays	41 (41.5)	22 (15.8)	5 (10.7)	68
	Totals	144	55	37	236

Figure B-32, Contingency Table for Day of Week and Weight Ranges, All Locations, 9:00AM – 3:00PM, Wednesdays and Thursdays, Class 6-7 Trucks

Location and Time Periods			Weight Ranges (000s of pounds)			
Location	Time of Day	Day of Week	< 30	30-40	> 40	Totals
I-20 Douglas County	7:00PM – 9:00AM	Tuesdays – Saturdays	230 (237.4)	85 (86.1)	75 (66.5)	390
I-75 Clayton County	7:00PM – 9:00AM	Tuesdays – Saturdays	45 (47.5)	17 (17.2)	16 (13.3)	78
I-75 Cobb County	7:00PM – 9:00AM	Tuesdays – Saturdays	127 (134.5)	50 (48.8)	44 (37.7)	221
I-85 S. of Airport	7:00PM – 9:00AM	Tuesdays – Saturdays	141 (123.6)	45 (44.8)	17 (34.6)	203
		Totals	543	197	152	892

Figure B-33, Contingency Table for Location and Weight Ranges, 9:00AM – 3:00PM, Tuesdays - Saturdays, Class 6-7 Trucks

Location and Time Periods			Weight (ranges (000s of pounds)			
Location	Time Period	Day of Week	< 30	30-40	> 40	Totals
I-20 Douglas County	3:00PM – 7:00PM	Mondays – Sundays	192 (199.4)	66 (70.9)	110 (97.7)	368
I-75 Clayton County	3:00PM – 7:00PM	Mondays – Sundays	105 (93.8)	24 (33.3)	44 (45.9)	173
I-75 Cobb County	3:00PM – 7:00PM	Mondays – Sundays	213 (224.4)	87 (79.8)	114 (109.9)	414
I-85 S. of Airport	3:00PM – 7:00PM	Mondays – Sundays	123 (115.4)	48 (41.0)	42 (56.5)	213
		Totals	633	225	310	1168

Figure B-34, Contingency Table for Location and Weight Ranges, 3:00PM – 7:00PM, Mondays - Sundays, Class 6-7 Trucks

Location and Time Periods			Weight Ranges (000s of pounds)			
Location	Time Period	Day of Week	< 30	30-40	> 40	Totals
I-20 Douglas County	9:00AM – 3:00PM	Mon., Tues., and Fridays	144 (147.9)	61 (60.9)	113 (109.2)	318
I-75 Clayton County	9:00AM – 3:00PM	Mon., Tues., and Fridays	106 (100.5)	42 (41.3)	68 (74.2)	216
I-85 S. of Airport	9:00AM – 3:00PM	Mon., Tues., and Fridays	10 (11.6)	4 (4.8)	11 (8.6)	25
		Totals	260	107	192	559

Figure B-35, Contingency Table for Location and Weight Ranges, 9:00AM – 3:00PM, Monday, Tuesdays, and Fridays, Class 6-7 Trucks

Location and Time Periods			Weight ranges (000s of pounds)			
Location	Time of Day	Day of Week	< 30	30-40	> 40	Totals
I-75 Clayton County	9:00AM – 3:00PM	3-4	92 (86.0)	34 (32.9)	15 (22.1)	141
I-85 S. of Airport	9:00AM – 3:00PM	3-4	52 (58.0)	21 (22.1)	22 (14.9)	95
		Totals	144	55	37	236

Figure B-36, Contingency Table for 9:00AM – 3:00PM by Location, Wednesdays, and Thursdays, Class 6-7 Trucks

Time Periods		Weight Ranges (000s of pounds)		
Time of Day	Day of Week	< 40	> 40	Totals
9:00AM – 3:00PM	Mondays	160 (161.9)	42 (40.1)	202
9:00AM – 3:00PM	Tuesdays	66 (76.9)	25 (19.1)	96
9:00AM – 3:00PM	Wednesdays	156 (160.3)	44 (39.7)	200
9:00AM – 3:00PM	Thursdays	135 (126.6)	28 (31.4)	158
9:00AM – 3:00PM	Fridays	193 (184.3)	37 (45.7)	230
	Totals	710	176	886

Figure B-37, Contingency Table for Day of Week and Weight Ranges, All Locations, 9:00AM – 3:00PM, Mondays - Fridays, Class 8 Trucks

Time Periods		Weight Ranges (000s of pounds)		
Time of Day	Day of Week	< 40	> 40	Totals
3:00PM – 7:00PM	Mondays	99 (92.0)	37 (44.0)	136
3:00PM – 7:00PM	Tuesdays	127 (128.5)	63 (61.5)	190
3:00PM – 7:00PM	Wednesdays	154 (161.0)	84 (77.0)	238
3:00PM – 7:00PM	Thursdays	158 (148.2)	61 (70.8)	219
3:00PM – 7:00PM	Fridays	125 (133.3)	72 (63.7)	197
	Totals	663	317	980

Figure B-38, Contingency Table for Day of Week and Weight Ranges, All Locations, 3:00PM – 7:00PM, Mondays - Fridays, Class 8 Trucks

Time Periods		Weight Ranges (000s of pounds)		
Time of Day	Day of Week	< 40	> 40	Totals
7:00PM – 9:00AM	Mondays	34 (29.8)	16 (20.2)	50
7:00PM – 9:00AM	Tuesdays	21 (18.5)	10 (12.5)	31
7:00PM – 9:00AM	Wednesdays	142 (147.7)	106 (100.3)	248
7:00PM – 9:00AM	Thursdays	49 (46.4)	29 (31.6)	78
7:00PM – 9:00AM	Fridays	82 (90.5)	70 (61.5)	152
7:00PM – 9:00AM	Saturdays	65 (60.1)	36 (40.9)	101
	Totals	393	267	660

Figure B-39, Contingency Table for Day of Week and Weight Ranges, All Locations, 7:00PM – 9:00AM, Mondays - Saturdays, Class 8 Trucks

Location and Time Periods			Weight ranges (000s of pounds)		
Location	Time Period	Day of Week	< 40	> 40	Totals
I-20 Douglas County	9:00AM – 3:00PM	Mondays – Fridays	143 (150.7)	45 (37.3)	188
I-75 Clayton County	9:00AM – 3:00PM	Mondays – Fridays	271 (259.6)	53 (64.4)	324
I75 Howell Mill Rd.	9:00AM – 3:00PM	Mondays – Fridays	224 (219.6)	50 (54.4)	274
I-85 S. of Airport	9:00AM – 3:00PM	Mondays – Fridays	72 (80.1)	28 (19.9)	100
		Totals	710	176	886

Figure B-40, Contingency Table for Location and Weight Ranges, 9:00AM – 3:00PM, Mondays - Fridays, Class 8 Trucks

Location and Time Periods			Weight Ranges (000s of pounds)		
Location	Time of Day	Day of Week	< 40	> 40	Totals
I-20 Douglas County	3:00PM – 7:00PM	Mondays – Fridays	177 (198.9)	117 (95.1)	294
I-75 Clayton County	3:00PM – 7:00PM	Mondays – Fridays	143 (105.5)	13 (50.5)	156
I-75 Cobb County	3:00PM – 7:00PM	Mondays – Fridays	165 (152.2)	60 (72.8)	225
I75-Howell Mill Rd.	3:00PM – 7:00PM	Mondays – Fridays	79 (60.9)	11 (13.9)	90
I-85 S. of Airport	3:00PM – 7:00PM	Mondays – Fridays	99 (145.5)	116 (69.5)	215
		Totals	663	317	980

Figure B-41, Contingency Table for Location and Weight Ranges, 3:00PM – 7:00PM, Mondays - Fridays, Class 8 Trucks

Location and Time Periods			Weight ranges (000s of pounds)		
Location	Time of Day	Day of Week	< 40	> 40	Totals
I-20 Douglas County	7:00PM – 9:00AM	Mondays – Saturdays	153 (171.0)	143 (125.0)	296
I-75 Clayton County	7:00PM – 9:00AM	Mondays – Saturdays	56 (53.1)	36 (38.9)	92
I-75 Cobb County	7:00PM – 9:00AM	Mondays – Saturdays	78 (74.5)	51 (54.5)	129
I-75 Howell Mill Rd.	7:00PM – 9:00AM	Mondays – Saturdays	24 (19.1)	9 (13.9)	33
I-85 S. of Airport	7:00PM – 9:00AM	Mondays – Saturdays	76 (69.3)	44 (50.7)	120
		Totals	387	283	670

Figure B-42, Contingency Table for Location and Weight Ranges, 7:00PM – 9:00AM, Mondays - Saturdays, Class 8 Trucks

Location and Time Periods			Weight ranges (000s of pounds)		
Location	Time of Day	Day of Week	< 40	> 40	Totals
I-75 Howell Mill Rd.	9:00AM – 3:00PM	Saturdays	8 (7.5)	3 (3.5)	11
I-20 Douglas County	9:00AM – 3:00PM	Saturdays	76 (76.5)	36 (35.5)	112
		Totals	84	39	123

Figure B-43, Contingency Table by Location for 9:00AM – 3:00PM, Saturdays, Class 8 Trucks

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