Measurement and Analysis of Traffic Loads across the Texas-Mexico Border

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16. Abstract

Axle load and gross-vehicle weight characteristics of Mexican-origin commercial trucks processed through the U.S. Customs yard in the City of Laredo, Texas, are described in this report. Investigation of these characteristics particular to Mexican-origin trucks is directed by a Texas Department of Transportation (TxDOT)-sponsored study entitled "Multi-Modal Planning and the U.S.-Mexico Free Trade Agreement" as a prerequisite to evaluating the potential damage to Texas highways posed by international trade traffic. Justifiable concern exists not just with the increasing volume of trade-related truck traffic, but also with the loads carried by Mexican-origin trucks. This study is facilitated by the installation of a weigh-in-motion (WIM) system at the preeminent Southwestern commercial truck port-of-entry (Laredo).

Load summaries are presented on five basic truck classes (by axle count) and are based on the original Association of American State Highway and Transportation Officials (AASHTO) pavement damage relationships. Load characteristics of each basic class include: 1) load status (empty or loaded), 2) ESAL factors (ESALs per truck), and 3) distribution of axle loads and gross-vehicle weights. Histogram summaries are provided for axle-group loads and gross-vehicle weights with the greatest propensity for exceeding current U.S. legal load limits.

Finally, damage implications are explored for the hypothetical integration of Mexican-origin commercial traffic, typified by that currently crossing at Laredo, and by that typified in a 1991 Mexican truck weight survey, into the current Texas traffic population.

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Research Report Number 1319-1

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Multimodal Planning and the U.S.-Mexico Free Trade Agreement

conducted for the

Texas Department of Transportation
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IMPLEMENTATION STATEMENT

As the United States, Canada, and Mexico harmonize truck size and weight legislation under the North American Free Trade Agreement (NAFTA), data on international truck weights will provide valuable information on truckers' ability to meet legal standards. The weigh-in-motion systems described in this study, together with preliminary data from Laredo, provide valuable insights into international trucking compliance with Texas weight legislation.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

DISCLAIMERS

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SUMMARY

The purpose of this report is to measure truck loading characteristics of Mexican-origin trucks currently operating within the Texas U.S. (ICC) commercial zones. The relevance of this goal stems from the following: (1) heavy truck axle loads are the primary cause of pavement wear; (2) international commercial traffic processed through Southwestern ports-of-entry as a result of the liberalization of Mexican trade practices has increased dramatically since the mid-1980s; (3) this increase in commercial traffic is likely to continue at an accelerated pace now that NAFTA has been ratified; (4) Mexican axle load limits exceed U.S. limits by 10-17%, depending on the axle group type; harmonization talks may eventually lead to higher allowable axle loads and gross-vehicle weights in the U.S.; and (5) infrastructure in the Texas border region is inadequate for current levels of truck traffic; projections for required upgrades extend out 30 years and exceed $2 billion in costs.

Collection of axle loading data is facilitated by the strategic placement of a weigh-in-motion system outside the U.S. Customs yard in Laredo, Texas. A near-100% sampling of loaded northbound Mexican-origin trucks is obtained at the busiest highway port-of-entry along Mexico's 3,020-km (1,250-mile) border with Texas.

Loading analyses are conducted one each of five basic truck classes (axle counts 2-6). The original AASHO pavement damage relationships are used in relative damage assessments. Analyses on data collected to-date indicate that most trucks processed through this port-of-entry are in compliance with U.S. legal load limits. The notable exception is the 6-axle class, with as many as 50% of these vehicles exceeding allowable axle loads and gross-vehicle weight. These trucks, however, constitute less than 2% of the total observed truck population. Less than 5% of 5-axle rigs, which comprise about 60% of the observed daily truck population, exceed allowable axle loads and gross-weight limits.

A two-day sampling of truck traffic currently operating on Interstate 35 south of San Antonio is used as a reference traffic stream is assessing potential increases in damage to Texas highway pavement design of accurate forecasting of traffic growth rates versus increases in average axle loads is addressed. It is difficult to generalize increases in damage to bridges because of the need to consider bridge span length, composition, and type, in addition to truck loading and axle spacing. A method for approaching such an assessment (Ref 1) is suggested.

Finally, a second report will be developed using the system described in this document and a large, two-way system installed as part of Study 1319 at El Paso. Annual data reflecting the full seasonal impacts will also be available to planners in this companion report.

CHAPTER 1. TRANSBORDER TRADE AND COMMERCIAL CARRIER OPERATIONS

There is a direct correlation between the volume of trade conducted between the U.S. and Mexico and the level of transborder traffic needed to move trade products. Increases in the level of this trade has led to dramatic increases in freight traffic levels even without the ratification of NAFTA. Change in the volume of trade under NAFTA is a matter of great supposition; because of this it is difficult to define a precise relationship for corresponding increases in freight traffic volumes. Additionally, factors such as the adequacy of infrastructure and compatibility of truck size and weight regulations must also be considered.

1.1 EXPANSION OF TRADE UNDER THE OPENING OF THE MEXICAN ECONOMY

Until recent years, the Mexican government enforced rigid control over the internal economy in an effort to stimulate domestic production and increase Mexico's industrial independence. In the 1970s, this policy could be sustained "artificially" because of Mexico's oil wealth. However, in 1982, the oil market collapsed and Mexico was deeply in debt from heavy borrowing used to finance its economic expansion. After realizing that past economic policies were in large measure to blame for declining international competitiveness, Mexico sought to reduce reliance on its oil exports and stimulate the production and export of manufactured products. Mexico joined the General Agreement on Tariffs and Trade (GATT) in 1986; import tariffs were drastically reduced and many non-tariff barriers eliminated. In addition, measures to reduce and eliminate restrictions to foreign investment were initiated (Ref 7). The administration of Mexican President Carlos Salinas de Gortari has set a sustained annual growth rate of 6% by 1994 as a goal, while reducing internal inflation levels to parallel those of its primary trading partners. Continued privatization of industry and encouragement of foreign investment are viewed as key strategies to achieve these goals (Ref 8). Finally, the 1994 peso devaluation may stimulate Mexican imports into the U.S., increasing the numbers of loaded northbound trucks.

1.1.1 Trade and the Border Customs Area

The U.S. is Mexico's largest trading partner, with roughly 75% of all Mexican exports destined for U.S. markets. Mexico is our third largest export market. By value, 90% of all U.S.-Mexico trade is transported by surface transportation, with 80% by value carried by commercial motor carrier (trucks) (Ref 9). In 1991, nearly 60% of the nation's exports to Mexico originated in or passed through Texas en route. Using 1989 data, approximately 87% (18 million tons) of southbound surface tonnage and more than 57% (9 million tons) of northbound surface tonnage passed through Texas. While more than 30% of the southbound freight is carried by rail, rail accounts for less than 10% of the northbound freight (Ref 2).

The U.S.-Mexico border area is divided into four customs districts. Two of these, Laredo and El Paso, lie almost totally within Texas (Fig 1.1). The Customs district of Laredo has the largest volume of commercial traffic, followed by the El Paso district. In 1990, roughly 85% of all truck traffic between Mexico and the U.S. passed through ports in the Laredo district, which processed more than 50% of all southwest border trade. Fifty percent of this trade (more than one-fourth of the total southwest border trade) passes through the City of Laredo alone (Ref 10).

Within the Laredo District, northbound truck traffic grew by a staggering 73% between 1986 and 1990, with rail traffic growing by an even more impressive 94% during the same period. West Texas ports process the largest volume of maquiladora-related freight. Truck-hauled freight produced in maquiladoras and other area industries account for 85% of all traffic that passes through the El Paso district. The number of northbound commercial trucks processed through El Paso has increased more than 100% from 1986 through 1990 (Ref 3). Figures 1.2 and 1.3 show the growth in northbound commercial truck and rail traffic within the southwest border customs districts.

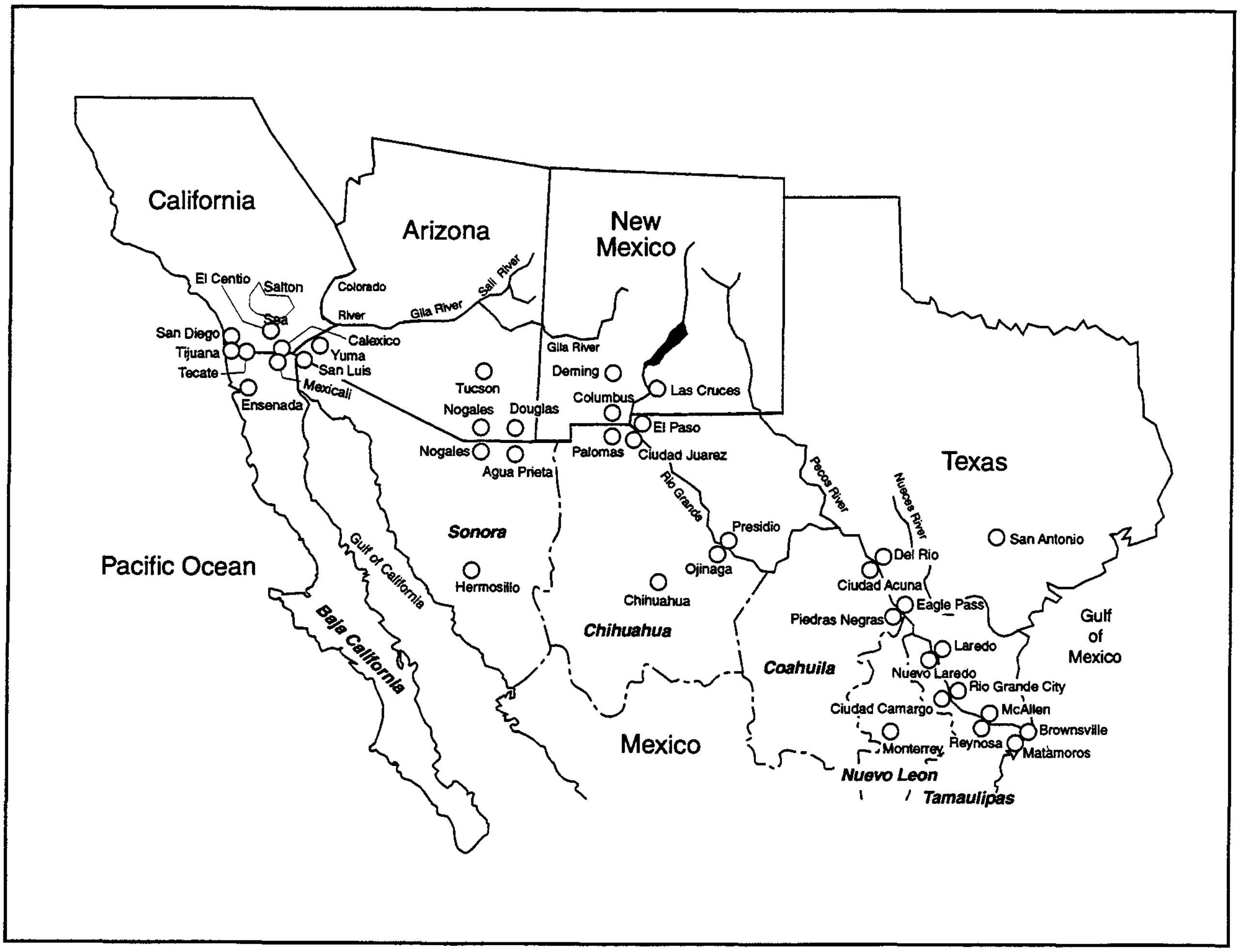


Figure 1.1 Southwest Customs Districts and Crossings

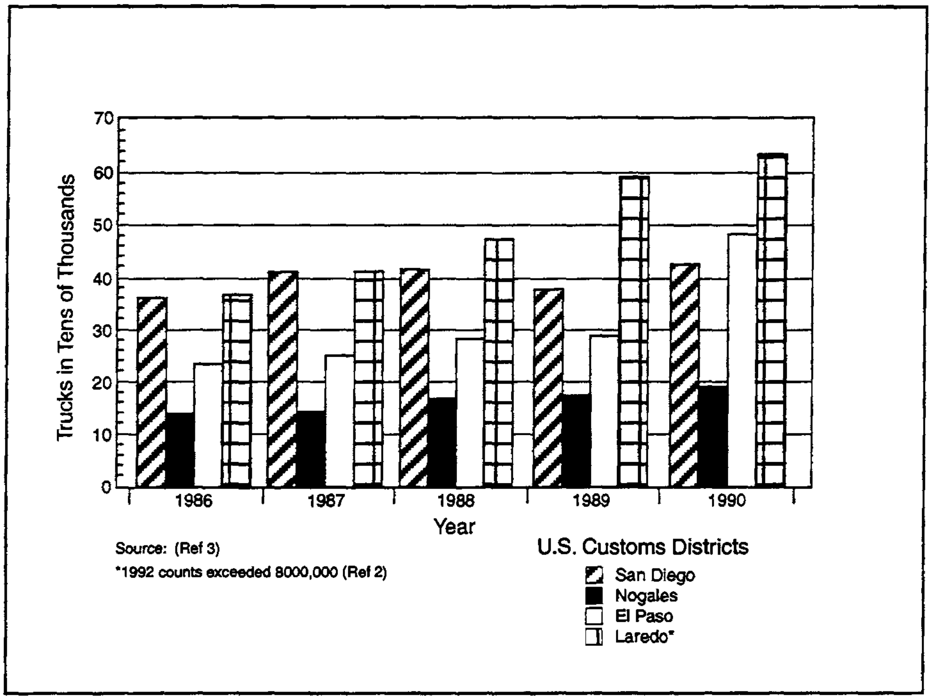


Figure 1.2 Northbound Trucks Processed at Southwest Border Ports

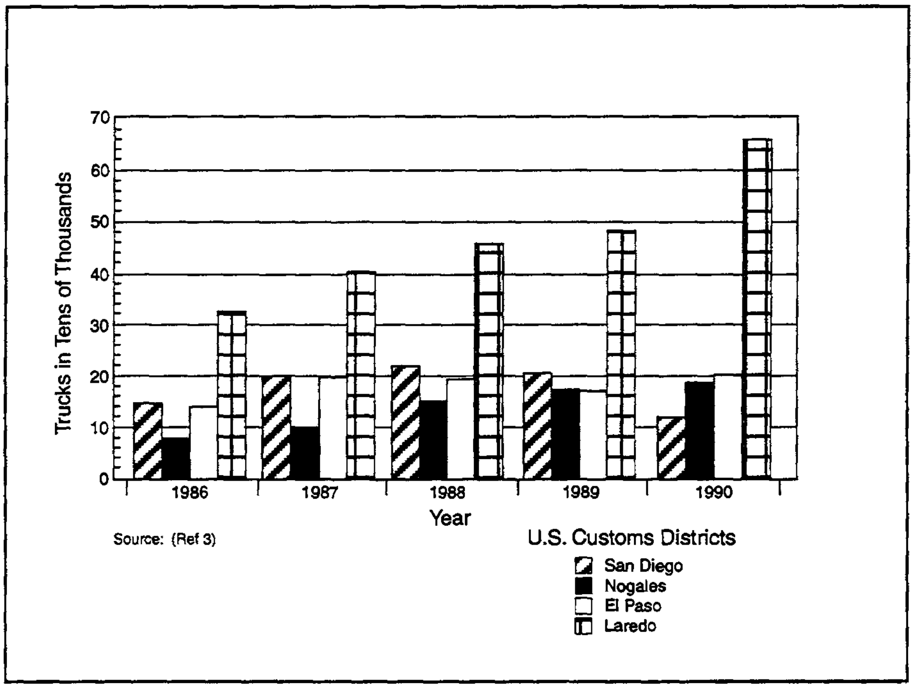


Figure 1.3 Northbound Rail Cars Processed at Southwest Border Ports

1.1.2 Impact of the Maquiladora Industries

As early as 1965, the Mexican government began to encourage U.S. manufacturing companies to locate factories in Mexico to stimulate employment in the northern border areas. These maquiladora industries consist of sister plants in the U.S. which send components to Mexico "in bond" or duty-free.

Products are then assembled in the Mexican plants. Originally, the agreement specified that assembled products would be intended for export only. U.S. tariff laws stipulate that for importation of these enhanced products to the U.S., duty is assessed only on the added value (Ref 10). The Mexican government has since allowed 20% (with special cases up to 50%) of the assembled products to be sold domestically. Nearly 95% of maquiladoras are U.S. owned, with approximately 80% of the plants located in inland areas of northern Mexico. Consequently, primary access to most is by overland freight (trucks), moved across inland highways. The maquiladora relationship has remained lucrative for U.S. companies, even in view of other sources of low-paid labor in many Asian countries, because the U.S.-Mexico proximity also means low shipping costs. Growth of the maquiladoras has been very pronounced, especially following successive devaluations of the peso in 1976 and 1982; today there are nearly 2,000 assembly plants employing close to a half million workers. By some estimates, as much as one-half of all non-petroleum-related trade (one-fourth of the total trade by value) between the U.S. and Mexico can be linked to these industries. Maquiladora exports crossing the Mexico-Texas border in 1990 were valued at approximately $8 billion, about 65% of total maquiladora exports (Ref 8).

1.1.3 Land-Routed Trade Trends Under a Ratified NAFTA

Even without the ratification of NAFTA, levels of trade are expected to continue to increase, following trends which began in the late 1980s. Most experts believe that NAFTA will only reinforce the existing trend, but estimates of the degree of escalation have been highly varied and speculative. In a University of Texas Study (Ref 7), a five-year projection for the period immediately following ratification cites an increase in Mexican exports to the U.S. of 3-4%. Estimates for increases in U.S. exports to Mexico in this time period are 9-14%. Estimates for increase in exports to Mexico from Texas are even more highly varied: a 4-29% increase over a ten-year period according to one study (Ref 7); up to 41% over five years and 74% within 10 years (above 1990 levels) according to another study (Ref 8). A third study suggests an increase of 19% (to $1.8 billion) in exports of manufactured goods within 10 years following ratification (Ref 11). In the first three months under an implemented NAFTA (January through March 1994), U.S. exports to Mexico rose by 16% while U.S. imports from Mexico rose by 22% (Ref 12).

The Government Services Administration (GSA), which manages the construction of customs facilities, has planned to increase customs facilities to accommodate a 100% increase in commercial traffic over the 10-year period 1990-2000. To formulate an estimate of traffic growth, GSA considered the growth rate of counts of trucks processed through ports during the period 1986-1990. These rates varied from a minimum of only 5% at several ports to 18% at Laredo.

An annual growth rate of 7% was used, which produced the 100% traffic growth planning factor (Ref 9). This 7% growth factor may appear rather conservative, especially considering the growth rates in Laredo, which is the single largest processing port. If an annual growth rate of 18% were used, a five-fold increase in truck traffic would be realized over this ten-year period. However, further escalation in the level of truck-hauled freight related to increases in overall trade activity may be moderated by the degree of success in resolving "harmonization issues" involving environmental protection, safety regulations, and truck size and weight standards, and the improvement in supporting infrastructure. Discussion of harmonization issues is projected to begin now that NAFTA has been ratified. Two-hour delays caused by inadequate customs facilities and staffing, as well as insufficient highway and bridge infrastructure, are already daily occurrences at the Laredo port.

The North American Free Trade Agreement would make maquiladora industries indistinguishable from other Mexican production plants. Popular belief is that most maquiladora industries would not relocate under NAFTA because of their proximity to U.S. inputs and markets (Ref 7). Maquiladora industry support structure has driven a high degree of integration of the respective border economies, which rely primarily on surface transportation (trucking) for their vitality. Relevant considerations for maintaining the status quo include decreased requirements to upgrade Mexican infrastructure, proximity to U.S. infrastructure, lower transportation costs, and the opportunity for managers to live in the U.S. (Ref 8). However, in recent years, changes in Mexican government policy which allow for the sale of higher percentages of value-added products locally have encouraged maquiladoras to establish themselves further in the Mexican interior, closer to large local markets and supporting infrastructure. Interior locations also provide for a more stable and educated labor pool.

While the volume of rail freight had been on the decline for many years, restructuring and a commitment to prevent further gouging by the trucking industry have recently allowed for moderate gains. Innovative partnerships and agreements with the Mexican national railroad, Ferrocarriles Nacionales de México (FNM), and Mexican trucking and shipping firms have set the stage for significant future expansion. In addition, intermodal arrangements between Union Pacific, Santa Fe, and Burlington Northern with motor carriers such as J.B. Hunt and Schneider National have bridged rivalries and allowed for joint expansion. Under NAFTA, rail service will continue to move bulk items (chemicals, petroleum products, food products, stone, etc.) more efficiently than motor carrier. Also, railroads are increasingly becoming the leader in shipping automobile components. Union Pacific anticipates the U.S.-Mexico market will increase at the rate of 15% per year (Ref 2).

1.2 PROCESSING OF INTERNATIONAL FREIGHT ACROSS THE TEXAS-MEXICO BORDER

Access to U.S.-Mexican territories by respective trucking fleets is controlled by a phase-in process under NAFTA. Currently, access to Mexican carriers within the U.S. is restricted to operating within commercial zones established by Section 226 of the Motor Carrier Safety Act of

1984. Conversely, American carriers are generally denied access to Mexico by Mexican laws which restrict commercial use of the country's federal highways to native Mexicans. Commercial zones within the U.S. vary in size and are determined by straight line distance "about the corporate limits of border municipalities" (Ref 13) according to the populations which live within their respective boundaries. Limits vary in size in accordance with Table 1.1.

Table 1.1 U.S. Border Commercial Zone Size

Population of Municipality	Commercial Zone Size (miles)
Less than 2500	3
2500 - 24,999	4
25,000 - 99,999	6
100,000 - 199,999	8
200,000 - 499,999	10
500,000 - 999,999	15
1,000,000 or larger	20
Source: (Ref 13)	

Note: 1.6 km = 1 mile

At present, Texas allows "private" Mexican motor carriers unregulated access to the entire state. Private motor carriers are those carriers which are owned by a parent manufacturing plant which transports their own product. There are currently no similar exceptions allowed for private U.S. carriers in Mexico. However, U.S. owners of maquiladora plants in Mexico have been allowed to use their own carriers to transport unassembled components and final products across the border since 1989, when deregulation of the Mexican trucking industry was implemented. In addition, several U.S. firms have been able to negotiate special transporting rights with Mexican based affiliates (Ref 2).

Mexican carriers operating within a U.S. commercial zone must first obtain a certificate of registration from the Interstate Commerce Commission (ICC), which is issued only to carriers who comply with U.S. equipment safety standards, are current in their payment of U.S. highway tax obligations, and have insurance to operate in the U.S. They are allowed to transfer freight between a single-point origin in Mexico and a single-point destination in the U.S (Ref 10).

Within three years of signing of NAFTA, December 17, 1995, Mexican carriers will be allowed unrestricted access to all territory of the four bordering U.S. states. Coincidentally, U.S. carriers will be allowed reciprocal access to the six northern Mexican border states, which, as previously stated, contain the majority of the maquiladora plants. Six years following ratification, all national territories will be opened to carriers on both sides of the border.

1.2.1 Truck Freight

As indicated above, national policies generally prohibit direct point-to-point cross-border freight transportation between one country and the other. There are two procedures used to overcome this inconvenience: interlining and interchanging agreements (Ref 7). Interlining involves a contractual relationship between U.S. and Mexican carriers which generally entails the U.S. carrier unloading cargo at the border where a Mexican carrier will complete the freight transport within Mexico. Interchanging is somewhat more efficient in that it allows the U.S. carrier to transfer the loaded trailer directly over to a Mexican tractor, eliminating the transloading process. The trailer is effectively "loaned out" (a bond is posted) with no formal contractual liability as used in the interlining process. There is some risk of damage to U.S.-owned trailers and often no opportunity for arranging a loaded shipment on the back haul, which translates into lost income for both sides.

Southbound freight is in general processed across the border by Mexican owned "freight forwarding" companies, which may own tractors or contract services from a drayage company. Drayage companies are also largely Mexican-owned. Their equipment fleets consist principally of older rigs which are adequate for the border crossing short-haul demands. In-house customs brokers generally handle required customs processing and may consolidate shipments and arrange for their U.S. clients the transfer to Mexican truck lines. Otherwise, brokers may arrange for transportation connections as an independent contractor. Of great importance to expediting the merchandise transfer across the border is early notification to the forwarding company/broker by the carrier to allow for preparation of customs documentation and payment in advance of crossing the border. Once the freight forwarder receives word that the load is cleared, the truck proceeds southbound. A Shipper's Export Declaration is presented to U.S. Customs; the truck is then met on the Mexican side by a representative of the Mexican customs brokerage who matches the manifest with the import documents and presents them to the Mexican customs officer. The Mexican customs computer determines whether the U.S. cargo will be inspected, with percentages of cargoes inspected based on the category of merchandise. When released from customs, the U.S. load is taken to the Mexican carrier's yard, where a Mexican tractor is substituted to complete the haul (Ref 8).

Northbound truck-hauled freight shipments are brought by a Mexican carrier into a transfer yard where a tractor from a drayage company is connected to conduct the cross-border haul into the U.S. Mexican export documents are presented to clear Mexican customs. Some large production plants in the interior of Mexico are authorized to ship cargo sealed in trailers by Mexican customs at the source, allowing for by-pass of Mexican customs at the border. A Mexican customs broker will provide a U.S. customs broker with a hard copy or electronic copy of the export documentation; the U.S. broker in turn inputs the information into the U.S. Customs centralized data base. The truck proceeds to the U.S. import lot where the U.S. broker will match documentation prepared at the broker office with that carried by the driver. An import inspector will scan a document bar code which is tied to a customer history database and indicates whether the cargo is to be inspected. The inspector has the authority to override the computer's inspection status recommendation. Trucks with cargo to be inspected proceed to a customs import lot. Once the truck has been cleared, paperwork is returned to the broker, who has 10 days to pay customs duties. A truck carrying Mexican-origin cargo can then proceed to the broker's yard if the load requires verification, re-packaging, or transfer to another carrier; or it may proceed directly to a U.S. carrier's yard, where the drayage company tractor will be replaced by a U.S. carrier's tractor. For intermodal service, the trailer can also be delivered to the intermodal yard for transfer to rail.

Prior to being allowed to proceed outside the commercial zone, trailers from Mexico are weighed at U.S. carrier yards or the intermodal yard to ensure compliance with U.S. federal weight regulations. Reducing overweight loads to comply with regulations is the responsibility of the freight forwarder or the customer (Ref 8). It is believed that no weighing is conducted on northbound commercial truck traffic prior to crossing the border.

Truck traffic related to the maquiladora industry (particularly to those plants within a 28-kilometer [17-mile] Mexican border zone) can conduct transborder shipping operations in a slightly streamlined fashion. U.S. trucks can deliver cargo to these plants without switching to a Mexican carrier. Maquiladora traffic destined for the U.S. may be directly transported across the border where it will be delivered over to a U.S. carrier, or a local transfer company may conduct the transborder movement as discussed previously (Ref 8).

Current transborder crossing by commercial carriers is quite inefficient, but is considered beneficial to local commerce as it provides a source of employment and considerable revenue and business. Hence, local communities may not be too interested in drastic changes. Passage of NAFTA may not in itself provide incentive for major changes. Even if duties were phased out, requirements still exist to certify "rules of origin," in addition to other enforcement responsibilities. The trade agreement does not address restructuring or combining respective nations' customs operations, but rather, "respects the autonomy of each" (Ref 2).

1.2.2 Rail Freight

Cross-border processing procedures of rail-carried freight have become increasingly streamlined by the use of customs pre-clearing measures. Southbound shipments require customs clearing on the U.S. side only. The broker's agent will send notification once Customs has cleared the shipment and the rail cars proceed across the border to their ultimate rail destination. Processing of northbound shipments can be expedited by faxing the invoice to the U.S. broker who can pre-file these documents with U.S. Customs. Once the rail cars cross the border, Customs determines if the shipment is eligible to proceed or if it must be verified. Railcars which are not pre-cleared are sealed by Customs and held at the railway yard until the broker provides required documentation. The use of sealed containers is also becoming more popular as a means to by-pass the border congestion and postpone inspection until a Mexican rail terminal is reached (Ref 8).

1.2.3 Joint Ventures in Transborder Freight Shipment

There are currently several unique partnership arrangements between U.S. and Mexican carriers which serve to facilitate transborder cargo shipment procedures discussed above. Celadon (U.S.) has fostered a long-term relationship with Hermes (Mexico); these firms have jointly created a holding company which has allowed for transfer of more modern U.S. equipment to Hermes, allowing for development of similar transport fleets on both sides of the border. A special interlining and interchanging arrangement has been facilitated through a measure of equipment standardization. J.B. Hunt Transport jointly established a Mexican subsidiary with

Fletes Soleto to service maquiladora plants. This now-defunct relationship evolved into a new coalition with Transportación Maritíma Mexicana (TMM) which gives the U.S. firm access to the Mexican interior using Mexican tractors. Intermodal agreements described previously with major railroads allow for more rapid transfer of cargo into Mexico by the Mexican national railroad (FNM). J.B. Hunt has also investigated the possibility of using truck-barge intermodal service out of Houston. Other U.S. carriers have established partnerships with Mexican carriers which feature single billing for door-to-door deliveries within Mexico, as well as automated rate and shipment locator information services (Ref 2). Expansion of efforts similar to those described above holds perhaps the greatest promise for streamlining transborder freight operations in the short term.

CHAPTER 2. TRUCK SIZE AND WEIGHT REGULATIONS AND TRANSPORTATION INFRASTRUCTURE MANAGEMENT

Currently, there is a total absence of conformance between U.S. and Mexican truck size and weight regulations. To complicate matters, states within the U.S. are allowed to set their own standards for all highways other than Interstates, and may exceed Federal load limits on Interstates if these limits existed prior to 1956 (Ref 14). The issue of conformity is scheduled for resolution now that NAFTA has been ratified, but the responsible committee may take up to three years to recommend standards, coinciding with the phase-in of unrestricted commercial vehicle travel in adjacent international states. Both Mexican and Canadian truck weight regulations allow for significantly higher loads than U.S. and Texas law. For example, Mexican tandem axle groups, the most common format for long-haul trucks, have a permissible maximum load which is more than 16% greater than the corresponding limit under U.S. federal law; the 5-axle tractor-semitrailer rig has a corresponding maximum allowable gross vehicle weight (GVW) exceeding U.S. legal limits by 14% (Table 2.1). With pressure likely from neighbors on both our southern and northern borders, the U.S. and Texas may well be faced with higher allowable vehicle loads in the future.

2.1 WEIGHT REGULATIONS

The Mexican federal government establishes vehicle regulations, a practice which provides for uniformity throughout the nation. The Secretariá de Comunicaciones y Transportes (SCT) oversees this function through the Dirección General de Autotransporte Federal (DGAF). This agency further classifies each highway by type (A, B, C, D) and stipulates which type (classification) of vehicle is allowed to travel on each highway based on allowable axle loads and GVWs. Type A roads are considered "high type" pavements which are comparable to those on major U.S. highways. Type B and C roads are comparable to lesser rural highways (e.g., two-lane Texas FM roads) and have reduced geometric design features such as narrow shoulders, lanes, and radii of curvature. Type D roads are generally not surfaced and are suitable for local delivery only (Ref 15). Type A roads allow the highest axle loads and GVW, and the trucks which are allowed to travel on these highways are the types which are most likely to participate in international trade (Table 2.1).

Revisions to current Mexican weight and size regulations are scheduled to be implemented beginning in November 1994 (Ref 17). Reductions in GVW are addressed in terms of a scheduled phase-in program spanning two years. However, the first phase scheduled to be implemented actually entails substantial *increases* above current allowable gross weights. On average, 3-, 4-, and 6-axle tractor-semitrailer combinations involve a 42% increase over current GVW allowances. The 5-axle tractor-semitrailer combination increase is nearly 23% over current standards. The final phase of reductions still leaves the allowable GVWs on the order of 6% above current levels for these classes of trucks which will most likely make up the bulk of transborder commercial motor traffic. No changes are specified for axle loads; one must assume that their allowable loading is proportional to the changes in GVW over current authorizations. The logic behind this revision of standards appears to be linked to an attempt to phase in stricter enforcement policies.

Table 2.1 Axle Load and Gross Vehicle Weight Regulations (lbs)

Axle/Truck Combination	U.S. Standards	Mexican Standards
Single axle (2 tires)	[1] None specified	12,100
dual (4) tires	20,000	22,000
Tandem axle (dual tires)	34,000	39,600
Tridem axle (dual tires)	[2] None specified	49,500
Tractor trailer rig with:		
5-axles	80,000	91,300
6-axles	80,000	101,200
7-axles	80,000	135,300
8-axles	80,000	143,000
9-axles	80,000	171,000

[1] All single axles are grouped together under U.S. and Texas law. Most States control this load by limiting the load per inch of tire width for each tire. In Texas, the limit is divided into two categories: 600 lb./in. for high pressure tires, 650 lb./in. for low pressure tires, placing the effective load limit for this axle type in the 12,000 lb range (Ref 16).

[2] 42,000 lbs. is generally used, as a result of direct application of the bridge formula.

After: Table 3.10 (Ref 2)

Note: 1 lb=0.453 kg; 2.5 cm =-1 inch; 1.6 km = 1 mile

Current U.S. weight standards were established under an amendment to the Federal Aid Highway Act in 1974 and apply to all roads receiving federal assistance. Limits for single-axle, tandem-axle, and gross vehicle weight are specified; in addition, a bridge formula, $W = 500 \times \left(\frac{LN}{(N-1)} + 12N + 36 \right)$ regulates the maximum load placed on any one axle group or adjacent axle groups (Table 2.1). In this formula, W is the allowable load or GVW, L is the distance between the extreme axles, and N is the number of axles in the group under consideration. Texas law regulating vehicle loading essentially follows federal guidelines (Ref 16).

2.2 SIZE REGULATIONS

In the U.S., prior to 1982, truck size limits were essentially a state concern. Federal regulations governing some aspects of truck size were established as part of the 1982 Surface Transportation Assistance Act and 1984 Tandem Truck Safety Act. The former included minimum length limitations designed to prevent states from establishing more restrictive limits on routes designated as belonging to the National Network (Ref 18). In Table 2.2, the variation in basic allowable truck dimensions between the two countries can be seen; Mexican trucking firms suffer a slight disadvantage against U.S. firms in the allowable trailer sizes. This has caused some concern on the part of Mexican carriers who would be operating less efficiently when competing directly against U.S. carriers, or would be faced with extensive costs to upgrade their fleets (Ref 2).

Table 2.2 Vehicle Size Regulations (ft)

Vehicle/Trailer	U.S. Standards (Texas)	Mexican Standards
Length:		
Single unit	None specified (45)	40
Semitrailer	48 [1] (59)	48
Trailer	28.0[1] (28.5)	30
Tractor semitrailer	None specified (none)	55.8
Road train[2]:		
Truck w/full trailer or	None specified (65)	72.2
Tractor semitrailer w/trailer	None specified (None)	92
Width	8.5[3] (8.5)[3]	8.5
Height	None specified (14)	13.6

[1]These are minimum lengths. Maximum lengths are not designated (Ref 16).
[2]Texas law limits these combinations to a total of "three vehicles", i.e., a truck or tractor and no more than two trailers (Ref 16).
[3]Regulations specify this maximum limit as 102 inches (Ref 16).
After: Table 3.9 (Ref 2)
1 ft=0.304 m

Longer vehicles, especially "road trains" consisting of tractors pulling multiple trailers, are generally equipped with more axles than single-unit trucks or tractors pulling single trailers. This feature often has the complementary effect of reducing individual axle loads, the primary source of pavement damage (Chapter 3), even though the GVW may increase. An argument has been made by Turner (Ref 19) and others to allow for increases in the current GVW cap, based on using longer vehicles with lower individual axle loads which could increase trucking productivity without increasing damage to pavements. Generally, opponents of longer vehicles cite safety as the primary detractor. Diversion of freight from rail service is viewed as a minor concern since railroads generally handle commodities with less urgent delivery schedules.

2.3 COMPLIANCE WITH WEIGHT LIMITS

A study conducted in 1991 indicated that Mexican weight regulations which were effective at that time were routinely violated due to lack of enforcement (Ref 20). Analyses conducted indicated that nearly 30% of the 18-wheeled (5-axle) tractor-trailer combinations exceeded legal weight standards on average by 18%, and over 40% of the 6-axle combinations pulling semitrailers equipped with tridem axles were overweight on average by 28%. When it is recalled that a fully-loaded Mexican truck operating under "legal" conditions has axle loads 10 - 17% heavier than a legally loaded U.S. truck, it becomes apparent that these overloaded vehicles can cause very significant pavement damage. For example, if the 18% average overload for GVW is used, and assuming a corresponding 18% increase in each of the allowable axle group loads, the average overloaded Mexican 5-axle vehicle would cause about three and one-third times as much damage as a legal fully-loaded Texan 5-axle rig (see Chapter 3).

Mexican commercial motor carriers are not alone in their apparent blatant disregard for weight standards. Texas Department of Public Safety (DPS) officials have been unable to effectively discourage U.S. offenders because of lack of dedicated resources and wholesale disregard for regulations by U.S. trucking firms (Ref 21). The absence of a penalty system with "teeth" encourages continued abuse; minimal fines are often seen as "the cost of doing business." A 1979 study published by the GAO suggested that approximately 15% of all loaded trucks are overweight with respect to allowable axle loads or GVW (Ref 22). This figure does include vehicles with overweight permits. Results of a more recently published questionnaire distributed to state enforcement agencies indicates that between 10 and 25% of all trucks are overloaded (Ref 22).

2.4 INFRASTRUCTURE ASSESSMENT

Since highway freight transport plays such an important role in facilitating the expansion of trade, it is necessary to examine the current adequacy/condition of highway infrastructure. Without adequate highway infrastructure, significant expansion of highway freight operations is not possible.

Concerns exist on both sides of the border regarding infrastructure adequacy under both existing and future levels of trade. One analyst summarizes the situation this way: "One of the most significant impediments to maximizing benefits of free trade will be the poor public infrastructure of southern Texas and northern Mexico" (Ref 11). Governments on both sides of the border have developed infrastructure improvement programs designed to accommodate growing trade traffic.

2.4.1 Mexican Infrastructure

Currently, a very small percentage of the existing Mexican network is suitable for sustained use by commercial motor carrier. In 1992, four-lane high-type pavement roads composed just 3,160 km (1,960 miles) (1.5%) of the total paved system. Of this, only 832 km (515 miles) (less than 0.5% of the total) are non-toll facilities (Ref 2). In general, paved state and federal roads do not receive adequate funding for maintenance. The design life of a typical Mexican pavement structure is 15 years; increased traffic, combined with relatively high allowable axle loads and lack of overweight enforcement, has led to accelerated deterioration. Beginning in 1989, the approach used by the Mexican government to upgrade Mexico's highway system uses a combination of public and private funding. Heavy reliance is being placed on the development of toll roadways on a concessionaire basis. This approach has met with mixed results; completed high quality highways generally have very high tolls, which has led to route avoidance and the further deterioration of alternate highways. Loss of toll revenues in turn reduces the financial backer's profits and contributes to a reluctance on the part of investors to participate in other planned projects. Another source of investment has been established through the use of user-financed trust funds established by the Mexican national trucking association and the Mexican tourism and passenger transportation organization (Ref 2).

The Mexican government continues to try a variety of approaches to entice commercial truck drivers onto the toll roadways, including decreasing tolls (requiring extension of concession terms), and conducting persuasion campaigns to convince freight haulers that the tolls are ultimately less costly to operators than the damage incurred by trucks from driving on poorly maintained toll-free roads. Even with the recent increased pace of highway infrastructure investment, it is estimated that it will take 20 years before the Mexican highway network will support projected levels of interborder commercial truck traffic (Ref 8). Shortcomings in the overall condition of Mexican highway infrastructure and the shortage of low-sulfur fuel rank as major concerns for U.S. motor carriers operating in Mexico (Ref 15).

2.4.2 Texas Infrastructure

Within Texas, increased attention is being focused on the current condition of, and improvements to, the infrastructure in the immediate border area. Truck concentrations have already reached very high levels within the major population hubs. A TxDOT study proposes a 30-year highway development plan for a four-lane divided highway system (Texas Highway Trunk System) comprised of the Interstate system and selected improvements to other highways, based on corridors which are likely to be affected by NAFTA (Ref 9). The Trunk System is ultimately designed to expedite traffic between larger centers of population and connect major ports of entry in adjacent states and Mexico. Just to meet current needs, roughly $850 million is recommended for improvements in the border regions, with an additional $1.2 billion for the Texas Highway Trunk System. The study also addresses accommodating a potential 100% increase in traffic by the year 2000 due to continued trade growth independent of or under NAFTA. This increase in traffic was determined to require the additional expenditure of approximately $50 million to previously identified border area projects and $75 million to the trunk system (Ref 9). A breakdown of funding requirements by Texas border area and varying levels of projected 10-year traffic growth is shown in Table 2.3.

There is reason for concern over the condition of existing pavements in Texas, especially in border regions. Overall, the condition of Texas highways declined in 1990 over serviceability levels of the late 1980s. This trend can be attributed partially to decreases in maintenance and rehabilitation funding, accompanied by an increase in truck traffic. The level of funding for border areas appears to have been especially low; much of the available funding went directly to the City of Laredo, which continues to experience phenomenal growth. When compared against funding received per lane-mile (1.61 km = 1 mile) in Eastern Texas (over $800/lane-mile in some areas), Laredo received between $400 and $599/lane-mile (1.61 km = 1 mile), while the rest of the border area received between $0 and $399. Further increases in the volume and loading of heavy trucks will only exacerbate serviceability degradation along the border unless more resources are focused on pavement and bridge rehabilitation (Ref 2).

Table 2.3 Projected Costs (1990) for Texas Border Region Highway Projects*

Border Area	Number of projects	1990 Costs	Costs at four levels of projected increases (percent) of commercial motor traffic			
			10	25	50	100
El Paso	12	$513	$517	$522	$527	$538
Del Rio	1	9	9	9	9	9
Laredo	6	127	127	129	133	135
Rio Grande Valley	25	94	95	96	97	101
U.S. 281	9	106	107	108	110	113
Subtotal	53	$848	$855	$864	$876	$897
Trunk System	26	$1,180	$1,192	$1,207	$1,224	$1,256
Total	79	$2,028	$2,047	$2,071	$2,100	$2,153

*Millions of dollars Source: Ref 9

2.5 INFRASTRUCTURE MANAGERS' CONCERN REGARDING OVERWEIGHT TRUCKS

The ability of transportation infrastructure facilities to support a specified design load or number of load repetitions is a fundamental concern of the facility designer. As such, it is critical that the designer know the load characteristics of the anticipated traffic over the targeted useful (design) life of the structure. In the U.S., pavements are typically designed for an economic life of 20 years; high-quality pavements generally require periodic refurbishing to return the serviceability (ride quality) to near-new conditions within this economic life. Bridges are typically designed with an economic life of 75 years (Ref 14). Periodic refurbishing of the deck and protective treatments applied to the superstructure against adverse environmental effects are also accomplished routinely. Because many existing facilities are subjected to combinations of higher-than-expected loads and/or greater numbers of load repetitions than originally designed for, these facilities are subject to premature deterioration of the ride quality and overall structural integrity. This scenario requires earlier-than-anticipated maintenance, rehabilitation, or replacement, which most often translates into unprogrammed expenditures of less-than-robust public resources. With existing highways, some compensation for heavier loads can be made through the use of overlays. However, structural strengthening of bridges, especially reinforced or prestressed concrete spans, is not a feasible alternative (Ref 14). In those undercapacity bridges which can be strengthened (primarily steel structures), the cost of strengthening is often a significant part of the cost to replace the entire structure. If future increases in the size and number of load repetitions can be estimated and related to those which currently exist, an estimate can be made of the relative decrease in the expected pavement and bridge service life. One approach to these relationships will be explored in Chapter 6.

CHAPTER 3. THE EFFECTS OF TRAFFIC LOADING ON PAVEMENTS AND BRIDGES

Engineered structures are generally designed to accommodate a combination of live and dead loads, including highway pavements and bridges. While bridges may be subjected to critical loading from environmental sources such as wind and their own structural weight, traffic loading, especially by heavy trucks, constitutes the primary source of critical loads on pavements. In the U.S., dramatic increases in the quantity of truck traffic and the magnitude of loads carried by this growing truck population was evidenced following both World Wars. The number of trucks tripled to 3.5 million from 1919 to 1929 over pre-World War I figures. Following World War II, the number of trucks doubled to 10.5 million between 1945 and 1955 from pre-war amounts (Ref 6). By 1992, there were nearly 45.5 million trucks registered in the U.S. logging 630 billion miles (1.61 km = 1 mile), averaging about 14,000 miles (1.61 km = 1 mile) per truck. Of the total trucks registered in 1992, 1.3 million were truck tractors. Combination trucks logged 99 billion miles (1.61 km = 1 mile), an amazing 76,000 miles (1.61 km = 1 mile) per tractor, or roughly 13 round trips across the continental U.S. (Fig 3.1) (Ref 23).

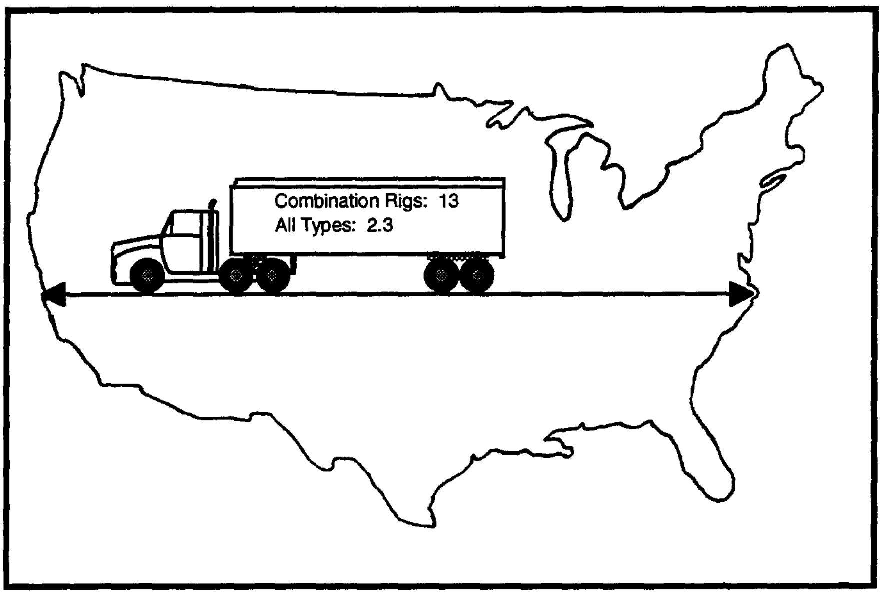


Figure 3.1 Average Round Trips Made by U.S. Registered Trucks (1992)

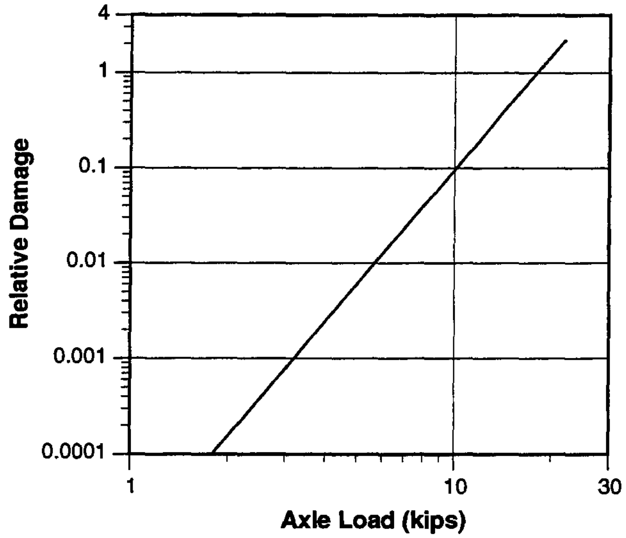
3.1 LOADING DAMAGE TO PAVEMENTS

Highway engineers recognized more than 70 years ago that a principal design consideration in developing a pavement with adequate structural support must be the anticipated *axle* loads of the expected heavier vehicles. This was in part intuitive, since a vehicle's load is carried through the axles to the wheels and then through tires in contact with the roadway surface. Early attempts to determine relationships of axle loading to design resulted in field experiments such as the Bates Experimental Road Tests between 1922 and 1923. General relationships which were developed from these early tests led to the adoption by 35 states of axle or wheel load limits by 1930 (Ref 6). Through the years, general relationships were also developed pertaining to effects of high versus low pressure tires and single- versus dual-tired wheels. It became very clear following World War II that the significant increases in both the magnitude and frequency of heavy axle loads were causing a significant escalation in the deterioration of roads which had been built for lighter loading. However, pavement experts could not agree as to what combination of factors contributed to the damage.

In the early 1950s, an amalgamation of industry and government agencies was formed to determine answers to a broader scope of issues related to "maximizing the overall economy of highway transportation" (Ref 6). The two primary issues involved studies which related vehicle size and weight aspects to the economical optimization of highway-transported freight, and the determination of the effects of axle loadings on pavement behavior. Investigation of this second issue eventually resulted in the American Association of State Highway Officials (AASHO, now AASHTO) Road Test conducted from 1958 to 1960 near Ottawa, Illinois. The AASHO Road Test was the most extensive controlled pavement testing ever conducted on test sections constructed specifically for research purposes. At a cost of $27 million, the study was billed as a "complete factorial experiment" which took years of planning and construction prior to initiation of testing operations under traffic in October 1958.

One of the most significant results of this study was the development of the concept of assessing damage to pavement based on equivalent single axle loads (ESAL). An 8,180-kg (80-kN) (18,000-lb) 18-kip axle with dual tires was chosen as the "standard" axle. That is, for one passage of the 8,180-kg (80-kN) (18-kip) axle, one unit of damage to the pavement can be assessed. A series of empirical equations, associated with pavement construction type, was developed using regression analysis which related several factors — pavement thickness or structural capacity, the terminal condition at which the pavement is no longer considered serviceable, axle configuration, and axle loading — to the number of axle passes required to produce a measured change in condition or serviceability. These equations determined the astonishing "fourth power" damage relationship, an approximation of the escalation of damage when comparing any axle load against the damage caused by the passage of a standard 8,180-kg (80-kN) 1(8-kip) axle. For example, a single axle loaded to 10,000 kg (98 kN) (22,000 lbs), a 22% increase over the standard 18-kip loaded axle would cause (98/80) or 2.23 times as much damage as the standard axle (Ref 6). Similarly, using this relationship, an axle which is just 10% overloaded would cause 46% more damage than one at the legal limit. A comparison showing the relative damage of a fully loaded truck axle to that of an automobile is often made using this relationship; it would take 10,000 - 818-kg (8.0-kN) (1.8-kip) automobile axles to cause the same damage as a single 8,180-kg (80-kN) (18-kip) truck axle (Fig 3.2).

Despite the conclusions of the AASHO Road Test and the intuitive notion that a vehicle's total load must be transferred to the pavement through loads placed on each axle, most agencies responsible for enforcing truck overweight restrictions do so on the basis of gross-vehicle weight (GVW) and not axle loadings. To an engineer, this policy is one of administrative expediency which has little relationship to financial accountability for those responsible for the preponderance of pavement damage.



Source: Ref 24

Figure 3.2 Fourth Power Law for Single Axles

3.2 AASHO PAVEMENT DAMAGE RELATIONSHIPS

The first of five objectives of the AASHO Road Test specifically addressed the goal of identifying statistically significant relationships between the quantity of axle loads ("... of differing magnitude and arrangement ...") on the *performance* of various cross sections (Ref 6). The dependent variable for these relationships was the parameter called "performance," whose definition was developed as part of the study. Carey and Irick (Ref 25) proposed that performance is a function of a pavement's ability to serve traffic over time. This relationship was dubbed the serviceability-performance concept. Thus, pavement performance is a history of serviceability over time or traffic loading; its deterioration is a measurement of damage from the original "new" condition. A five-point descriptive scale was established to define relative degree of serviceability based on the notion that, "a good highway is one that is safe and smooth" (Ref 25). In practice, a panel of raters (representative of the general public) subjectively appraises the serviceability of a section of pavement. These individual ratings are averaged to produce a present serviceability rating (PSR). Because it is impractical to evaluate large quantities of pavement in this manner, the concept further entails objectively measuring surface roughness (variations in the longitudinal and transverse profiles), and combining the values mathematically so as to predict the PSR. This value is known as the Present Serviceability Index (PSI), and also ranges between 0 and 5, with five being perfectly smooth. The AASHO Road Test showed that approximately 95% of information related to the level of serviceability is contributed by roughness (Ref 26). In a summary of the AASHO Road Test, one conclusion was that, "... terms relating specifically to distress (cracking, patching, and rut depth) can be ignored" (Ref 27).

The original AASHO pavement performance equations are used in this study for simplicity and generalization not requiring considerations of varying roadbed resilient module or reliability for varying levels of traffic used in design of pavements for a specific location. The primary independent variables used in the original equations are the pavement design (rigid or flexible), axle configuration and loading, the number of axle load applications and the terminal serviceability levels. For flexible pavements, over time interval t, an axle group carrying a specified load requires W_t load applications to reduce the serviceability to level P_t (serviceability index at time t). The equation is expressed in logarithmic form as:

$$\log W_t = 5.93 + 9.36 \log(\overline{SN} + 1) - 4.79 \log(L_1 + L_2) + 4.33 \log L_2 + \frac{G_t}{\beta}$$

where:

$\overline{SN}$ is the pavement structural number, and = $a_1D_1 + a_2D_2 + a_3D_3 \ldots$, where $D_1, D_2, D_3, \ldots$ are layer thicknesses and $a_1, a_2, a_3, \ldots$ are layer coefficients related to the type of material used in each layer. Values for $\overline{SN}$ range from 1 to 6;

L_1 is the axle/axle group load in kips;

L_2 is the axle group code (1 for single axle, 2 for tandem, 3 for tridem);

G_t is the logarithm of the ratio of loss in serviceability at time t to the potential loss at an unserviceable index level established at the Road Test as 1.5. $G_t = \log\left[\frac{4.2 - P_t}{4.2 - 1.5}\right]$

P_t is often equated with the terminal serviceability, typically 2.0 - 2.5, when evaluating pavements for maintenance and rehabilitation. The Road Test also established an initial "new" flexible pavement serviceability index level at 4.2 (average value for those constructed for the Road Test).

β is a function of the design and load variables which influences the shape of the performance curve (serviceability vs. the number or load repetitions).

$$\beta = 0.40 + \frac{.081(L_1 + L_2)^{3.23}}{(\overline{SN} + 1)^{5.19} L_2^{3.23}}$$

Similarly, for rigid pavements,

$$\log W_t = 5.85 + 7.35\log(D+1) - 4.62\log(L_1 + L_2) + 3.28\log L_2 + \frac{G_t}{\beta}$$

where variables are defined as before with the following additions or changes:

D is the thickness of the concrete slab in inches;

$$G_t = \log\left[\frac{4.5 - P_t}{4.5 - 1.5}\right]$$

$$\beta = 1.0 + \frac{3.63(L_1 + L_2)^{5.20}}{(D+1)^{8.46} L_2^{3.52}}$$

Damage ratios were established comparing the relative damage caused by the number of applications of a selected axle, W_{t_i}, against the "standard damage" caused by a single 18-kip axle. This term is referred to as an equivalence factor, E_t (Ref 28). For flexible pavements,

$$E_t = \frac{W_{t_{18}}}{W_{t_i}} = \left[(L_i + L_2)^{4.79} / (18+1)^{4.79}\right]\left[10^{G_t/\beta_{18}} \Big/ \left(10^{G_t/\beta_i}\right) L_2^{4.33}\right]$$

where E_t varies with $\overline{SN}$, a factor in β, in addition to the axle group load and configuration. Similarly, for

$$E_t = \frac{W_{t_{18}}}{W_{t_i}} = \left[(L_i + L_2)^{4.62} / (18+1)^{4.62}\right]\left[10^{G_t/\beta_{18}} \Big/ \left(10^{G_t/\beta_i}\right) L_2^{3.28}\right]$$

rigid pavements, where E_t varies with slab thickness D, in addition to the applied load and configuration.

3.3 LIMITATIONS OF THE AASHO ROAD TEST

Some significant limitations to the general applicability of the AASHO damage relationships emanate from the lack of diversity in soil and climatic conditions of the test site, the limited diversity of materials used and the conditions under which they were placed, the limited range of axle loads, and the limited diversity of axle configurations, tire pressures, load applications, and pavement ages used. A host of follow-up studies have been conducted to mitigate the impact of these limitations and allow for more general applicability (Refs 6, 29, 30, 31). Many pavement researchers question the general applicability of the "fourth power" damage relationship and propose that a range of exponential values more closely approaches reality (Ref 29). Many pavement engineers believe the time has come to routinely employ more mechanistic approaches in evaluating pavement performance, based on analytical methods used to estimate the stress, strain, and deflections encountered by pavements under load. While state-of-the-art pavement analysis has been moving in this direction for some time, the AASHO empirical equations with modifications continue to be one of the most widely used tools in pavement performance analysis (Refs 26, 31).

3.4 GENERAL EFFECTS OF HEAVY VEHICLES ON PAVEMENTS

Perhaps the most important failure mechanisms in pavements are fatigue and permanent deformation. In flexible and rigid pavements, both the magnitude and overall volume of individual axle loads determine the degree of fatigue damage, which eventually results in cracking. Fatigue is controlled through choosing the appropriate pavement thickness based on expected axle loads. Limiting axle loads to the design criteria increases the probability that the pavement will perform as expected through its design life. Permanent deformation (rutting) is caused by further compaction of flexible pavement layers and plastic flow of the asphaltic concrete under loading. One study (Ref 29) indicates that the amount of rutting is directly proportional to the total weight of all trucks using the highway. The belief is that reducing the axle load or GVW limits will not reduce rutting if more trucks are required to haul the freight transferred off heavy trucks to comply with these reduced standards. The degree of rutting can be controlled by using asphalt mixes that are more rut-resistant, and to some degree by using thicker layers.

3.5 OTHER PAVEMENT DAMAGE CONSIDERATIONS

Research indicates there are several other physical characteristics of trucks and dynamic interaction considerations which make significant contributions to pavement damage. None, however, have been shown to have the first-order significance of axle loads (Refs 18, 29).

3.5.1 Truck Characteristics

Vehicle conditions which also contribute to accelerated pavement damage are:

(a) Axle Group Suspension Systems. Systems that do not allow equal static load-sharing result in the heavier axle causing a disproportionate share of the damage. Also, while most suspension systems cause dynamic loads comparable to their single-axle equivalents, some cause up to twice as much damage on roads with moderate-to-high roughness (Ref 29).

(b) Tire Pressure. Maximum tire pressures used during the AASHO Road Test were 550 kPa (80 psi). Higher tire pressures appear to accelerate fatigue damage in flexible pavements to a greater extent than in rigid pavements (Ref 29).

(c) Tire Configuration. The AASHO damage relationships were based on axles mounted with dual tires. Studies have shown (Refs 29, 30) that steering axles with their single tires cause more damage than an axle mounted with four tires carrying an equal load. The effect becomes pronounced above a 5,450-kg (53.4-kN) (12-kip) load; Carmichael's study indicates that an 8,180-kg (80-kN) (18-kip) load on a two-tired single axle delivers twice the damage (i.e., two ESALs) as the standard four-tired single axle.

3.5.2 Pavement, Age, and Environmental Characteristics

Conditions in these areas which contribute to accelerated damage include:

(a) Current Pavement Serviceability (roughness). Rougher surfaces cause greater excitation of loaded axles, which accelerates the overall rate of fatigue damage (Ref 29).

(b) Pavement Age. Since pavements built for the AASHO Road Test were new when the test started, reaching a maximum age of two years by the end of the study, the long-term effect of aging could not be assessed. The effects of aging when considered separately or combined with traffic loading and environmental affects are still not well understood (Ref 31).

(c) Temperature. Loads placed on flexible pavements experiencing high temperatures typical of daytime highs in the U.S. South and Southwest significantly increase pavement rutting. With pavement temperatures at 49°C (120°F), this damage may increase by a factor of 16. Temperature gradients seem to have a significant affect on fatigue damage to rigid pavements. A one-degree-per-inch of slab depth gradient may increase curling and warping effects (causing fatigue damage) ten times over a zero-gradient state (Ref 29).

(d) Trapped Moisture. Trapped moisture can be extremely detrimental to pavement life through a number of mechanisms, including soil swelling, frost heave, decreased subgrade/base strength, stripping, and pumping. Well-sealed wear courses and good internal pavement drainage can alleviate the preponderance of these effects (Ref 31).

3.6 GENERAL EFFECTS OF HEAVY VEHICLES ON BRIDGES

In comparison with pavements, bridge damage, potentially resulting in catastrophic failure, is much more alarming to the imagination of the motorist. Currently in Texas, 6,800 of 47,900 bridges in the total state-county-local system are posted as incapable of carrying the design vehicle load. Less than 10% of these are located on major highways maintained by TxDOT. Fifty percent of bridges in the Texas bridge inventory are over 30 years old (Ref 32). Although their original designers incorporated generous safety factors, increases in truck weights and volumes have substantially eroded the original margin of safety.

Bridge span length has a significant bearing on the relative proportion of the structure which must carry traffic (live) loads versus the load of the structure itself (dead load). Main structural members in a 12-m (40-ft) span may require 70% of their strength to support the anticipated traffic loading, whereas similar members in a 305-m (1,000-ft) span may require 75% of their strength to support the structure itself. Bridges with spans below 12 m (40 ft) are more sensitive to high axle group loads. For medium-length spans (12-46 m, or 40-150 ft), the GVW becomes the critical dynamic load. For spans longer than 46 m (150 ft), the structural dead load becomes the controlling support requirement to such an extent that vehicle live loads have little impact (Ref 33). For shorter spans, axle spacing and axle loads are significant factors as stress levels increase with weight concentrations over shorter axle intervals. For simply supported spans, stresses can be effectively reduced by increasing axle spacing and spreading the load over more axles. However, with continuous spans using intermediate supports, negative moments generated when a longer wheel-based vehicle straddles the intermediate support may result in higher stresses than produced by a shorter axle interval (Ref 14).

Overstress and fatigue are the two vehicle loading responses which are critical in evaluating the effects of overloaded vehicles on bridge structural integrity. Effects of loading on the decking (traveled surface) are similar to those already discussed for rigid pavements.

3.6.1 Overstress of Bridge Structural Members

This overloading response addresses the severe damage to member(s) caused by the occurrence of a single extreme loading. The greatest probability of this event occurring is the case in which two or more heavy trucks cross a bridge simultaneously. Furthermore, the distribution of vehicles on the bridge and their dynamic impact (a function of speed and decking roughness) may further exacerbate the criticality of the event. A safety factor is applied during design stages to minimize the probability of these combinations of loading events from happening during the bridge design life. For example, with steel beam structures, AASHTO (Ref 14) uses an "inventory" rating equal to 55% of the yield stress in critical members, and is defined by

$$0.55R = D + L(1 + I),$$

where

R is the limiting stress applied to the beam;
D is the stress resulting from the dead load;
L is the stress resulting from the live load;
I is an adjustment factor to the static effect of live loads to account for dynamic effects.

The AASHTO uses a similar safety factor equation for stress on steel beams for making crossing limitation (posting) decisions. Referred to as the "operating" rating formula, it was derived to prohibit the crossing of vehicles which would impose stresses exceeding 75% of the yield stress in the weakest member.

3.6.2 Fatigue of Bridge Structural Members

Like pavement fatigue, fatigue of bridge members addresses the cumulative effect of large quantities of loading cycles, which eventually may cause structural cracks or rupture of components. Each application of a stress cycle decreases the load supporting components' remaining fatigue life. With a bridge consisting of steel components, a "third power" damage relationship for applied stress exists (Ref 14). A truck that induces twice the stress relative to another will cause eight times the damage.

3.6.3 Relevance of the Federal Bridge Formula

The AASHTO uses a series of design vehicles with fixed static load characteristics to design highway bridge capacities. Most highway bridges designed prior to World War II were based on AASHO design vehicles designated as H-15 or H-20. These vehicles were 2-axle trucks weighing 30,000 lbs (15 tons) and 40,000 lbs (20 tons) respectively, each with a 14-foot wheel base and loads distributed 20% front axle/80% rear axle. During the 1940s, as tractor-semitrailer combinations became more popular, an HS-20 3-axle design vehicle with a variable rear axle spacing ranging from 4.3 to 9.1 m (14-30 ft) was adopted to develop design standards for continuous spans. Weight distribution for the HS-20 truck was 3,640 kg (35.6 kN) (8,000 lbs) on the front axle and 14,550 kg (142 kN) (32,000 lbs) on each of the two other axles. The axle spacing which produced the maximum stresses was used as the design spacing (Ref 14). With the continued increase in allowable vehicle loading, some states have adopted an HS-25 design which allows for loads 25% higher than HS-20 standards. Table 3.1 shows the design capacity distribution of Texas highway bridges on the state highway system.

Table 3.1 Texas Highway Bridge Capacities

Classification*	Quantity	Percent of Total
H(S)-10 or less	294	0.9
H(S)-12 to 14	555	1.7
H(S)-15 to 19	6,760	20.6
H(S)-20 or above	25,172	76.8

*Combination of H and HS designations

Source: Ref 34

In 1974, the federal government adopted the federal bridge formula (Ref 14) with a 36,360-kg (356-kN) (80,000-lb) GVW cap (see Chapter 2) to limit traffic-induced stresses to older bridges designed to H-15 and HS-20 standards (Ref 33). Most H-15 bridges are located on secondary routes, which generally carry little of the heavier long-haul truck traffic. The bridge formula was derived to limit over-stressing on these bridges to no more than 30% of assumed design stresses, a generous allowance balanced by low application frequency. On the other hand, the formula limits over-stresses to only 5% for HS-20 bridges, the preponderance of which are on primary routes or Interstates. These major routes carry the bulk of heavy truck traffic; this lower over-stress allowance is intended to protect the investment in these bridges by more strictly limiting excessive repetitive overloading.

CHAPTER 4. COLLECTING TRUCK WEIGHT DATA

Collection of truck weight data began in the mid-1930s; collection efforts intensified as the volume and magnitude of truck-borne freight loads dramatically increased in the post World War II era. Principal uses of the data were for enforcement of load-limit laws and, increasingly, as a basis for improving pavement design to consider load requirements. Portable static wheel-load weighers, referred to as loadometers, were employed by crews which diverted selected traffic out of the traveled lanes to conduct the weighing operation. Wheel loads were often taken only on one side of the truck; these loads were then doubled to estimate axle loads and summed to determine the truck's gross weight. This process was fraught with bias with respect to estimating either individual vehicle load parameters or load parameters of the truck population as a whole. Additionally, there were legitimate safety concerns for the weighing crew working in traffic; the process was generally inefficient, and freight hauling productivity suffered. Weighing stations using full-width static axle-load scales and vehicle scales were also established, but these enhancements still required diverting selected traffic from the normal traffic stream, causing delays to vehicles being weighed. Support infrastructure became a significant overhead cost in addition to the operating staff. Since most weighing operations had as their primary purpose the enforcement of vehicle weight regulations, by-passing or "waiting-out" the station's operating schedule by over-laden freight-haulers was common practice, which consequently added another bias dimension for pavement designers to reconcile (Ref 35).

4.1 WEIGH-IN-MOTION (WIM)

Although the estimation of a moving vehicle's individual axle loadings and overall weight is not a new concept, the evolution of practical WIM systems progressed relatively slowly, especially in comparison to applications of current technologies. For nearly two decades, beginning in the 1950s, the desire to make weighing operations more efficient and safe, while still maintaining reasonable accuracy, was hampered by the infancy of required technologies (Refs 35, 36, 37).

4.1.1 The Evolution of Weigh-in-Motion

While enforcement of weight laws was the principal objective of most early weighing operations, engineers were intent on using weight data to design better pavements by understanding the effects of applied axle loads. However, quantifying the relative contribution of specific causes of pavement failure was still beyond the capability of pavement managers because sufficient "representative" data had not yet been collected, and a working understanding of performance relationships between design standards, materials behavior, quality of construction, and load applications was still lacking (Ref 38). The deficiency regarding interrelationships of various performance phenomena was successfully addressed following completion of the AASHO Road Test (1958-1960) (Ref 6), with its resultant analyses. However, significant accumulation of traffic loading data was delayed until technology would allow automation to be applied to the weighing process.

The process of obtaining axle load data for moving vehicles began to be realized in the 1950s. The Bureau of Public Roads (predecessor of the Federal Highway Administration) developed a prototype full-lane-width "floating" weigh platform supported at each corner by columns outfitted with strain gage load cells (force transducers). The load cells were wired into a Wheatstone bridge circuit which generated an electrical potential differential in proportion to the applied (axle load) compressive force. By use of parallel circuitry to connect the four load cells, the total axle load on the platform could be estimated. Several WIM sites using similar technology were installed in the U.S., Europe, and Japan in the late 1950s and early 1960s (Ref 36).

These systems offered great potential for relieving the major detractions cited for static weighing operations. However, technological problems (including absence of compact automated data-processing equipment) plagued wide-spread acceptance of these and subsequent WIM systems until the early-to-mid-1970s. These early systems required up to about 10 seconds to obtain a complete vehicle reading on a storage oscilloscope. Manual analysis of the oscilloscope traces was then required to determine axle loads and gross-vehicle weight (GVW). The weighing platforms were inherently massive and stiff, with relatively large inertia, in comparison with the dynamic forces they were supposed to measure. As a result, the system was incapable of responding adequately to rapid force changes, such as would be caused by the passage of closely-spaced axles, or even of returning to a static state prior to passage of trailing axles. System installation, operations, maintenance, lack of portability, and protection of the sensors from moisture were all substantial shortcomings of these early devices (Ref 36). Further development of WIM systems focused on aspects related to greater portability, methods of capturing dynamic tire forces, and algorithms used in translating the dynamic tire forces into equivalent static loads.

4.1.2 Basic Operating Characteristics

Essentially, WIM systems perform two distinct operations: 1) detect the presence of a passing vehicle using sensors connected to supporting electronic processors and measure corresponding dynamic tire forces using transducers with respect to time and location; and 2) interpret dynamic-force measurements to produce estimates of static wheel and axle loads and gross-vehicle weight (GVW), and estimate speed, axle spacing and vehicle classification by axle configuration parameters (Ref 37). The more common forms of electrical "weighing" technology employ variations of strain-gage systems (load cells, bending plates), capacitive mats, and piezo-electric cables.

Certain precautions must be taken to ensure the validity of collected WIM data. The magnitude of a dynamic tire force applied to a given point on a pavement is highly variable in comparison to its static load. Dynamic tire force has been shown to range from double its static counterpart (e.g., when a tire encounters a bump), to zero, when the tire may accelerate upward and actually lose contact with the roadway surface (Ref 37). Tires which are not perfectly round or balanced also cause high variance in the vertical component of wheel accelerations. Conceptually, true accuracy and consistency in measuring dynamic wheel forces is most readily accomplished when vertical acceleration of all component vehicle masses are "zero". Under ideal conditions, the sum of the vertical components of all tire forces exerted on the horizontal surface would exactly equal the gross weight of the vehicle (Ref 37).

Practically, these exacting conditions can never be achieved; the only conditions which can be realistically regulated are the horizontal and vertical alignment and smoothness conditions of the stretch of pavement in the immediate vicinity of the WIM system sensors. Standards pertaining to these parameters were established by the American Society of Testing Materials (ASTM) in 1990. In addition, specifications pertaining to accuracy with respect to static vehicle weights by type of system, and for system calibration, are also delineated (Ref 28).

4.2 THE LAREDO WIM SYSTEM

As mentioned in Chapter 1, Laredo is one of the busiest ports between Mexico and the U.S. for processing of truck freight. As such, it is a logical location for characterizing the weight of Mexican trucks which are currently authorized to operate within the ICC ("commercial") zones. An extensive study has been made of interborder trucking operations at Laredo (Ref 8). Results of this study reveal that virtually all northbound loaded trucks must pass over a single bridge and be processed through an adjacent U.S. customs yard prior to being allowed to select a desired route on the local road network. This arrangement enables the use of a single strategically-placed weighing station to capture the preponderance of all loaded trucks crossing into the U.S. at this port-of-entry.

4.2.1 Background

Negotiations for a WIM site began with City of Laredo officials in late 1992. Initially, there was considerable concern by City officials regarding the potential negative impact that the study might have on the routine flow of local freight and on the thriving local retail business, especially if the operation was perceived to be law-enforcement related. The City has been witness to several blockade-type disturbances in the recent past. In April 1993, a meeting between Laredo officials, local TxDOT engineers, and representatives of The University of Texas at Austin was held to outline support relationships and obtain approval of a proposed WIM-system location. Preliminary reconnaissance of a prospective site 122 m (400 feet) west of the U.S. customs yard gate showed good potential; the existing roadway at this point ran straight for more than 122 m (400 feet) with no intersections other than an entrance to a city-owned parking lot (Fig 4.1).

This adjacent parking lot was outfitted with several luminaires, which assured a source of reasonably accessible electrical power for the WIM system. The existing pavement was a two-lane (one lane each direction) asphalt concrete structure measuring approximately 8.8 m (29 feet) wide, which carried the preponderance of northbound traffic westward from the customs yard. Concern regarding eventual rutting of the approaches to the weigh site by channelized truck traffic led to the subsequent proposal that the City replace a segment of the westbound lane (4.3 m, or 14 feet total width) with 0.3-m (12-inch) continuously reinforced concrete pavement (CRCP) for a length of 61 m (200 feet). This would help insure compliance with ASTM smoothness standards, at least for the duration of the two-year study. Once the City accepted responsibility for providing this upgrade, the most significant remaining shortcoming was the lack of a readily accessible telephone line required for remote monitoring of the WIM system and retrieval of data.

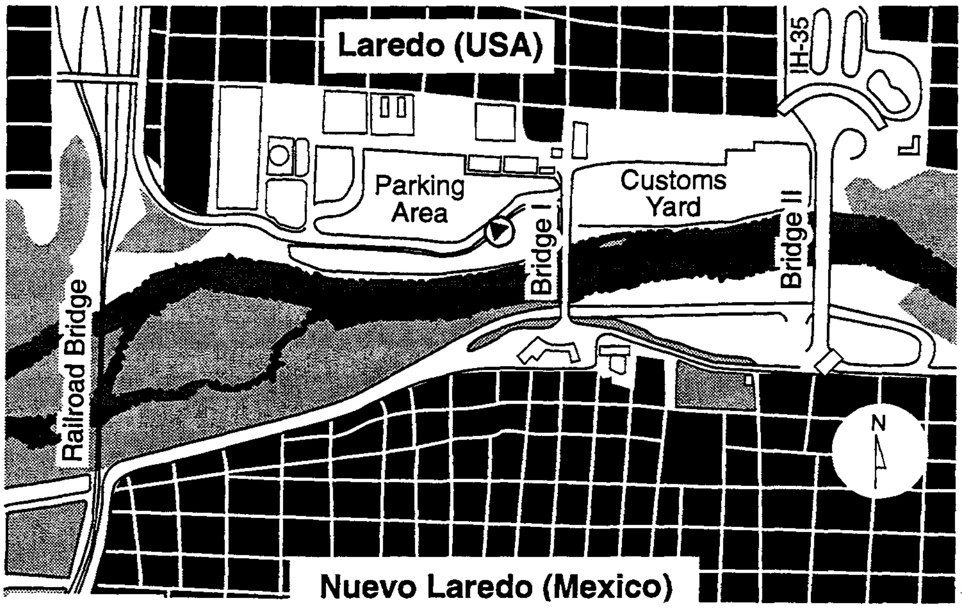


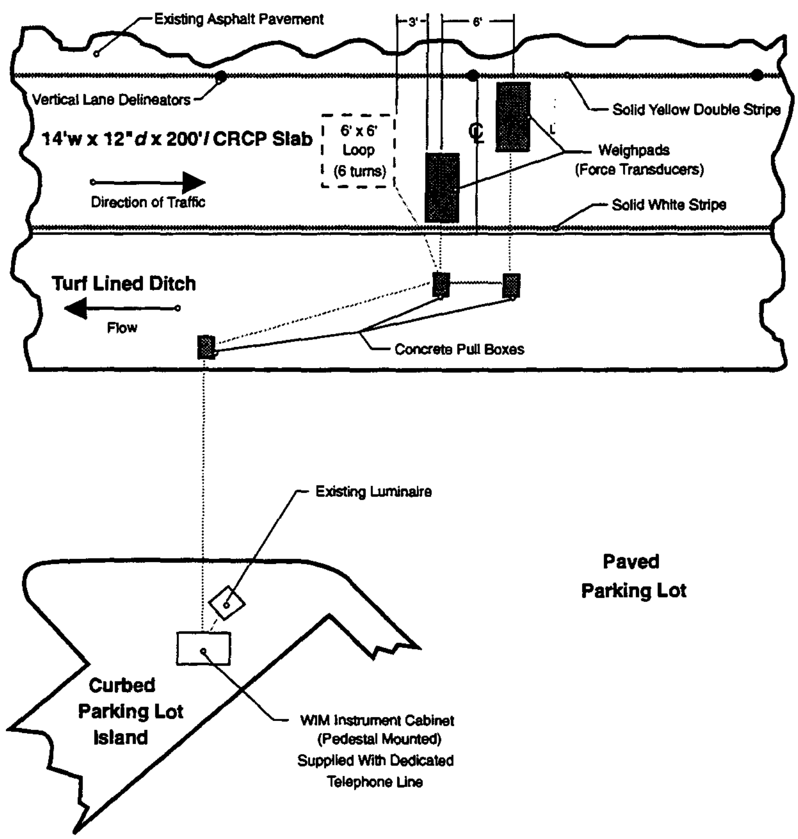
Figure 4.1 Location of the 1319 Study WIM site at Laredo (Ref 8)

4.2.2 Laredo WIM System Selection and Configuration

The WIM system chosen for the Laredo site was a PAT (Pietzsch Automatisierungstechnik) Equipment Corporation's DAW 100 system, selected because of a proven history of reliability and because of installation familiarity on the part of the TxDOT traffic monitoring systems installation crew. Configuration for use at the Laredo study site is shown in Figure 4.2.

Vehicle detection is accomplished using a standard 1.8-m-square (6-foot-square) inductive loop, which when "activated" initiates a new vehicle record. One weighpad is placed in each wheel path in a staggered pattern to allow calculation of vehicle speed and axle spacing, based on the known 1.8-m (6-foot) offset distance. The dynamics of the vehicle departure from the customs yard, proceeding from a complete stop, imply that the traffic will probably be accelerating when crossing the transducers (weighpads). Since this aspect has the potential of affecting the accuracy of the axle-load record produced, the algorithm used to process impulse signals from the weighpads determines the speed of each axle and calculates axle spacing by multiplying the average speed of two adjacent axles by the time interval between these axles arriving at one of the weighpads. A constant acceleration is assumed over this short time interval.

The transducers use "bending plate" technology, in which resistance strain gages are bonded directly to the bottom surface of narrow transverse grooves in a steel plate. These plates are encased in vulcanized rubber and supported along their long edges by a steel frame, which is anchored and epoxied into a shallow (51-mm-deep, or 2-inch-deep) pit cut into the pavement surface. The weighpads are mounted flush with the roadway surface so as not to introduce additional dynamic motion to the overpassing vehicle. The bending plate format assists in minimizing the overall mass of the weigh pads, eliminates the mechanical interface between the strain gage and the weighing platform, and minimizes pavement excavation depth. This last aspect has the benefit of reducing overall installation costs and avoiding interference with concrete pavement reinforcement.



Source: Ref 39

Figure 4.2 Project 1319 WIM Configuration at Laredo

The DAW 100 on-site processing unit is housed in a standard traffic signal controller system cabinet and is operated by a 12-volt DC power supply connected to a conventional 115-volt AC line power source.

4.2.3 Installation and Functional Layout

A contractor to the City of Laredo excavated a 61-m-by-4.3-m (200-foot-by-14-foot) segment of the existing pavement and replaced the section with a CRCP slab in late August 1993. A 102-mm (4-inch) asphalt-treated drainage base layer was prepared beneath the slab and extended approximately 0.9 m (3 feet) laterally into the adjacent ditch. The slab was allowed approximately three weeks to cure prior to cutting and excavating for WIM sensor installation. TxDOT's installation crew and a PAT-contracted installer installed the system hardware over a two-day period from 21 to 22 September 1993.

On the first day of installation, the longitudinal centerline of the 61-m (200-foot) CRCP section was determined and surface tracings locating in-pavement sensors and conduit channels were laid out, placing the weighpads symmetrically about the longitudinal center of the pavement slab (Fig 4.2). Concrete saws, a jack hammer, and rock pry bars were used to cut grooves for the inductive loop cable and to excavate the troughs for the weighpad frames and required conduit channels. An air compressor hose jet was used to blow loose debris from the cut areas. The weighpad frames were temporarily fitted into their respective pits to check for proper depth and to mark locations for anchors. Anchor holes were drilled using a percussion drill. Anchors were then positioned, through guide holes in the weighpad frames, into the previously drilled holes in the concrete slab. PVC pipe was cut to length and placed to house lead cables from the weighpads. Two-component epoxy cement was then mixed and worked into the anchor holes, between the cut pavement and the carefully-located frame, and around conduit channels, emphasizing the elimination of air voids from the fresh epoxy cement. The inductive loop was laid using standard stranded, jacketed loop wire in six turns. Silicone sealant was then applied to the groove to secure and weatherproof. A small walk-behind trenching machine was used to excavate channels for the cable leads across the turf ditch area between the road and parking-area pavements. The processor cabinet location with supporting cable trenches was laid out on a parking area island and across the parking area pavement. Pavement saws were used to trace required cable channels and to trace a cutout for the pedestal base of the processor cabinet with a linking channel to the existing luminaire, which would serve as a power source. A jackhammer was used to cut the cable conduit channels across the parking area, as well as the pedestal and channel cutouts on the island.

On the second day of the hardware installation, excess epoxy was ground off of the upper frame surfaces. The transducers were bolted in and a straight edge run across these and the adjoining roadway surface to check for local evenness. Shims were cut for low areas and placed between the transducer and frame to achieve a flush pavement/transducer interface. The transducer bolts were then torqued down and sealed with silicone sealant.

The City's Traffic Safety Department contracted for attachment of a step-down transformer to the luminaire electrical lines to supply the WIM-system processor cabinet with 115-volt AC power. Department personnel installed roadside pull boxes and completed the site cable routing in PVC pipe conduits. They installed the processor cabinet pedestal base anchor and refinished the channels cut into the concrete island, asphalt parking area, and turf ditch. Finally, the Department installed the pedestal base and arranged for telephone service to the site. Telephone service required the installation of an overhead line which was accomplished by mid-November 1993.

4.2.4 Site Commissioning

This phase was conducted in early October 1993, and consisted of three steps: 1) mounting the DAW 100 processor and system power supply in the controller cabinet, 2) mounting the cabinet on the pedestal, and 3) performing system initiation checks and calibration. Calibration was accomplished using a 3-axle TxDOT calibration truck with known axle loads/GVW and known axle spacings.

A PAT systems representative assisted in all aspects of the commissioning phase, as required by contract. Calibration proved to be the most time-consuming aspect of the commissioning process. Although just over 100 passes were made, the final adjustment and verification of measurements consistency involved only the final six runs. An analysis of this initial calibration is provided in Appendix A. It can be seen from the data shown that the values for GVW were within 6% of the static GVW; front axle loads were within 11% of the static axle load. Individual rear axle loads, when compared against their respective static loads, were within the 10-12% range. When considered as a tandem set, differences in axle-group load were within 7% of the set's static load. These results were well within the tolerances specified in *ASTM E 1318*, however, better results were anticipated for the typically low site speeds under controlled operating conditions.

A follow-up calibration session was conducted in early December 1993 using a 4-axle tractor-flatbed combination (FHWA Type "8") hauling a backhoe. This exercise required only very minor correction factor adjustments to those installed during the October exercise. An analysis of the results from this vehicle shows that the values for the GVW ranged within about 4% of the static weight; steering-axle results were within 8% of the static load, and the trailer-tandem load was within 6% of the static load (Appendix A).

CHAPTER 5. LAREDO WIM DATA SUMMARIES

As mentioned in Chapter 2, the typical Mexican commercial truck is generally believed to weigh more than its corresponding American counterpart because Mexican federal truck weight limits are considerably higher than corresponding U.S. limits, and there is evidence that a sizable percentage of Mexican vehicles exceed even these generous standards. Given this background, there has been legitimate concern about the load status of motor carriers coming north into Texas and operating within the U.S. commercial zones. Prior to the installation of the WIM in Laredo, no clear picture of northbound transborder motor carrier loading distributions was available.

In the Laredo case, strategic placement of the WIM system allows for a near-100% capture of northbound commercial traffic at the preeminent Southwestern land port-of-entry. Because of this condition, it was thought that no inference would need to be made about load distributions at this location. The possibility of producing accurate portrayals of truck class distributions and corresponding loading characteristics was first realized in early October 1993. However, the nature and significance of two shortcomings were not initially understood; a series of corrective actions continued through early June 1994. The first shortcoming involved the lack of proper lane tracking by trucks proceeding out of the customs yard; the second concerned default WIM-system software parameters which were set to values inappropriate for the relatively slow-moving traffic at the site. While the data which were collected prior to June 2, 1994, accurately reflected the loads crossing the transducers, because of the shortcomings cited, it is difficult to state with any degree of confidence how representative these loads were of the entire population and what types of loads are typically associated with a given type of truck configuration.

For these reasons, the six-week period from June 4, 1994, to July 15, 1994, will be the primary analysis time frame. Summaries will generally address weekday and weekends (Saturdays) separately. The record from the 4th of July, the only holiday falling within the analysis time frame, contained a disproportionately large number of files indicating empty trucks; it was excluded because its profile did not appear to fit that of either a weekday or a Saturday. Sundays were excluded because Customs operations are closed and the recorded traffic has questionable origin. Records from June 14, 1994, were excluded because a large percentage of records was lost during the on-site exchange of a DAW 100 processor EPROM.

Comparisons of data summaries from periods both before and after corrective actions were taken will be examined later in this chapter. Finally, trends in the generation of erroneous data files will be examined from both before and after corrective actions were taken.

5.1 ANALYSIS TOOLS

Data processing was conducted on a microcomputer (IBM compatible), using two software applications. The first application, developed in-house at The University of Texas at Austin, translated binary encoded records retrieved from the on-site DAW 100 processor into ASCII format. Once the files were translated, a series of Microsoft® EXCEL macros were developed to sort records by truck class and load-status, calculate ESALs, group load data for histogram presentation, and produce various summaries. The initial sort macro also extracted records containing various specified irregularities which made them inappropriate for further analysis as standard truck records.

5.2 TRUCK POPULATION COMPOSITION

As a preliminary sorting procedure, the raw database was split into records by axle count. Trucks crossing into Laredo generally fall into five axle-count categories (2 - 6), with a very small percentage (less than 0.5%) of combinations above six axles. Additionally, combinations entailing more than one trailer were found to appear quite infrequently. These last two categories are not included in the summaries which follow.

The current nature of transborder motor carrier freight operations entails the back-haul of a percentage of empty trailers into the U.S. (Chapter 1). Further dividing the database into categories of empty trucks and those with at least a partial load allows for the generation of a useful set of statistics. It was deemed to be more important to analyze records of loaded trucks in detail, as they cause the overwhelming proportion of highway damage. Once the initial phase of NAFTA has expired, profit incentives might make trucks with at least a partial load the more likely variety traveling long-haul on highways in Texas. Empty-weight thresholds were chosen to delimit load status within each predominant truck class. Table 5.1 shows the assumed empty-weight thresholds.

Table 5.1 Empty-Weight Thresholds

Axle Count	Empty Truck Must Weigh Less Than: (kips)
2	12
3	18
4	25
5	32
6	38

Two load-status summaries were prepared using records from the six-week analysis time frame. In Figures 5.1a and b, typical daily counts for empty and loaded trucks are portrayed, while in Figures 5.2a and b, weekly variations in daily distribution of truck-class and load-status are shown as a percentage of the total weekly or Saturday truck population. Numbers in parentheses are total counts for that week or Saturday.

On weekdays, as well as on Saturdays, loaded 5-axle trucks dominate, with loaded 4-axle combinations following a distant second. Empty 5-axle combinations constitute the third largest group.

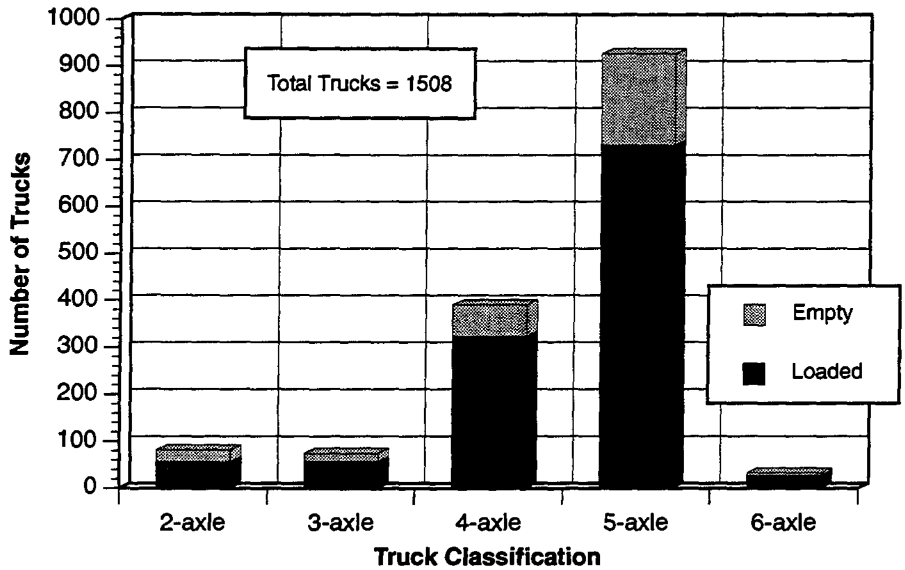


Figure 5.1a Average Daily Truck Counts (Weekday) by Number of Axles

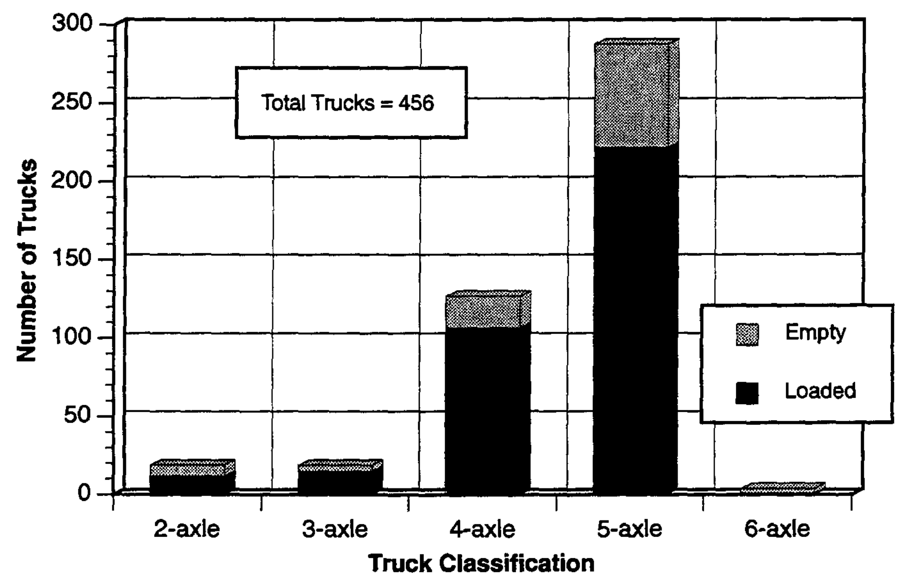


Figure 5.1b Average Daily Truck Counts (Saturday) by Number of Axles

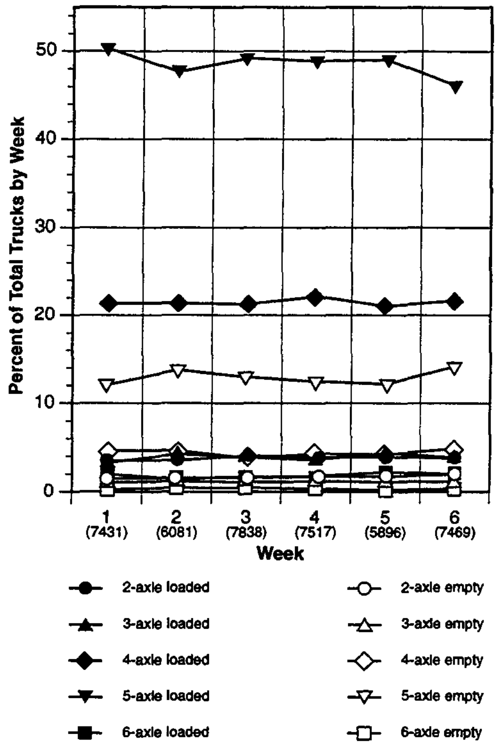


Figure 5.2a Average Daily (Weekday) Load Distribution

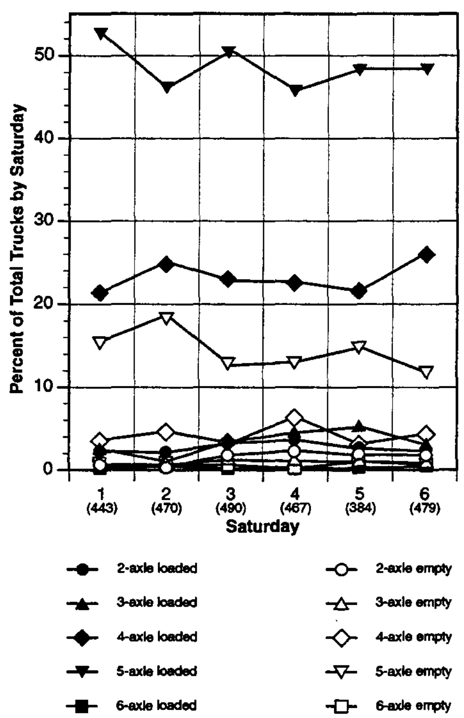


Figure 5.2b Average Daily (Saturday) Load Distribution

5.3 TRUCK LOADING PROFILES

U.S. load limits on Interstate highways for single and tandem axles (9,090 kg [89 kN] and 15,450 kg [151 kN], or 20 and 34 kips, respectively), and gross-vehicle weight (36,360 kg [356 kN] or 80 kips) were used in these analyses. In addition, a "maximum" of 12 kips was used for the steering axle as this value corresponds roughly with the maximum allowed when considering load per inch of tire tread width limits stated in Texas law. Also, a limit of 19,100 kg (187 kN) (42 kips) was used as the maximum permissible load on a tridem axle group through direct application of the federal bridge formula, assuming a 2.4-m (8-foot) interval between the first and third axles (Ref 16). It should be noted that tolerances are sometimes applied, particularly if enforcement is the objective. No tolerances were applied to summaries provided herein.

Next, axle loads and GVWs were converted into percentages of the allowable legal limit and histograms were produced for each axle group or GVW using bin increments of 10%. Steering axles for all truck classes were grouped together using one bin range, while the remaining axle groups and GVW were grouped by vehicle class using a second bin range. Aggregate profiles showing percentages of trucks (by class) observed during the analysis period relative to their steering axles' load (as a percentage of the allowable legal limit) are shown in Figure 5.3. Similar aggregate profiles covering the entire analysis period for the remaining axle groups and gross-vehicle weight, grouped by vehicle class, are presented in Figures 5.4 through 5.6 and 5.9 through 5.10. Observed numbers of trucks are shown in parentheses. Biweekly trends can be seen in Appendix B. These profiles enable detection of significant load violation trends at a glance. Readily apparent from the figures cited above is the fact that modal loads (axle and gross-vehicle weight) for all classes of truck are generally less than one-half of the legal limit, with the exception of loads on steering axles.

As seen in Figure 5.3, steering axle loads rarely exceed the informal maximum of 12 kips. Those exceeding this limit do so by relatively small amounts (i.e., generally by no more than 10%).

On 2-axle trucks, less than 2% of the drive-axle loads or gross-vehicle weights exceed U.S. legal limits (Figure 5.4). These same load parameters on 70 to 80% of these trucks are below 50% of the allowable. This condition may be a reflection of loads which tend to "cube-out" in these trucks which are primarily used for local delivery (i.e., between Nuevo Laredo and Laredo).

Data shown in Figure 5.5 relate that there are two principal axle configurations in the 3-axle truck class. The single unit variety constitutes approximately 83% of the total 3-axle population; the remainder consist of tractor-semitrailer combinations. The latter configuration in general shows little over-loading tendency. Within the 3-axle single unit (SU) configuration, the tandem-axle groups show some tendency for being overweight, with about 4% of these axle groups more than 10% above the legal limit. A corresponding aggregate tandem-axle group load profile, showing axle group distribution in kips, is presented in Figure 5.7. From this figure, it can be seen that the modal loading for this axle group is from 4,450 kg to 6,360 kg (44.5 kN to 62.3 kN) (10 to 14 kips); roughly 12% of the axles exceed the allowable 15,450-kg (151-kN) (34-kip) limit.

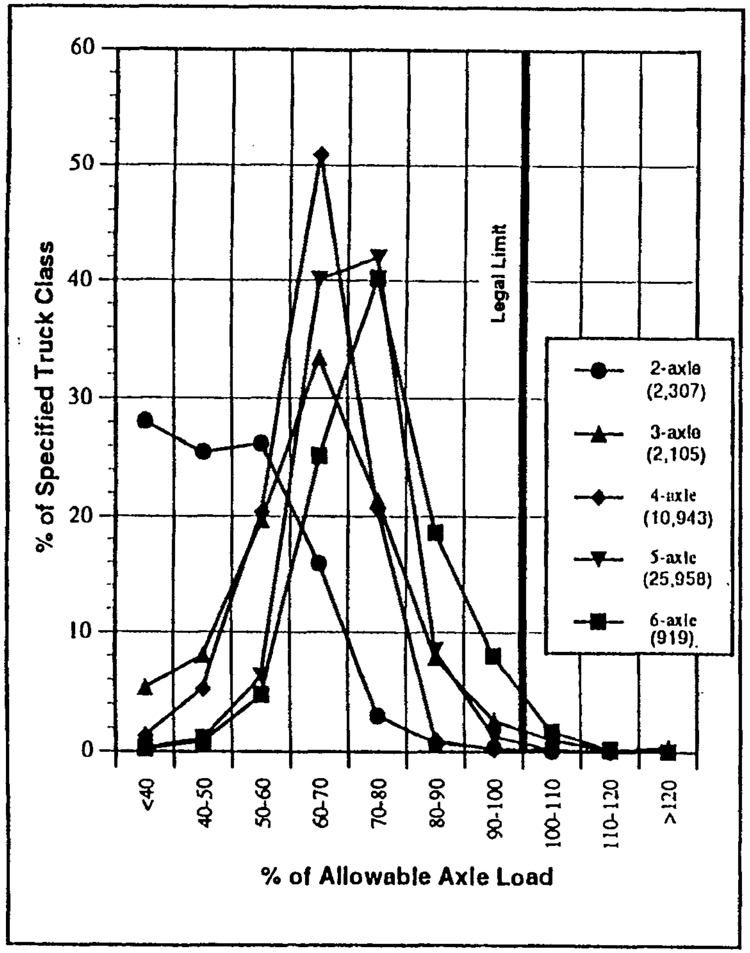


Figure 5.3 Steering-axle Loads: Weekday Aggregate Profile, 6 June – 15 July 1994.

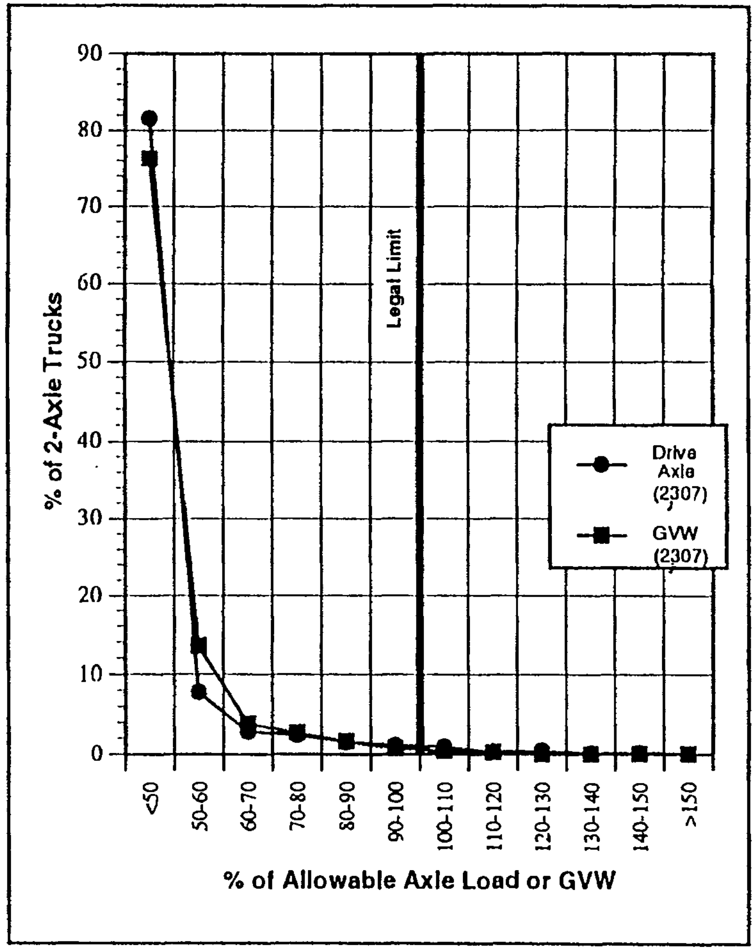


Figure 5.4 Two-axle Truck Loads: Weekday Aggregate Profile, 6 June – 15 July 1994.

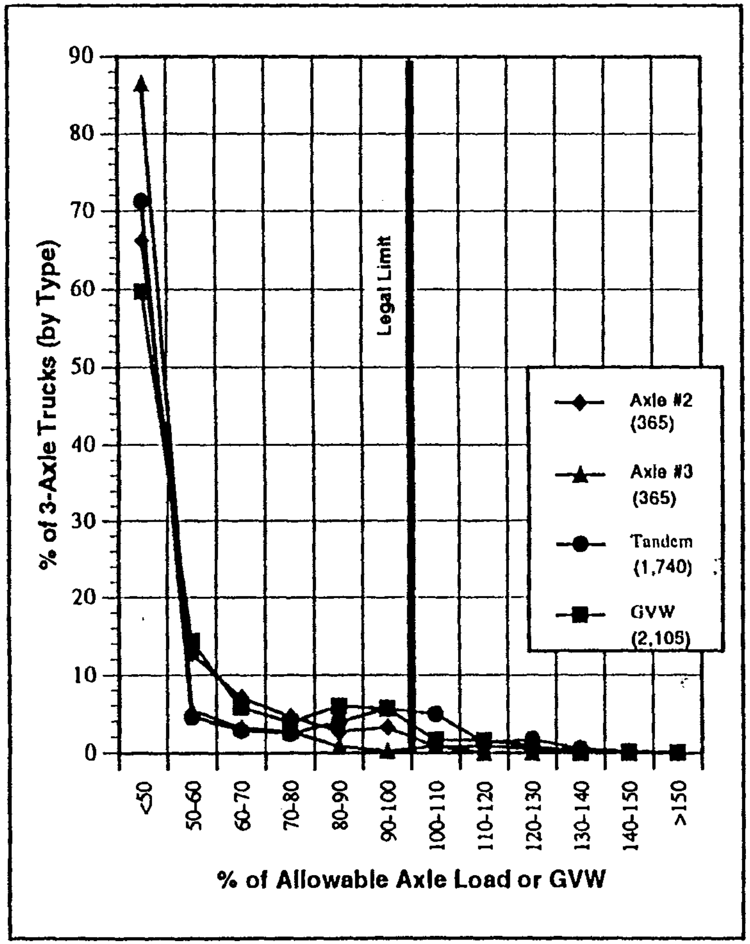


Figure 5.5 Three-axle Truck Loads: Weekday Aggregate Profile, 6 June – 15 July 1994.

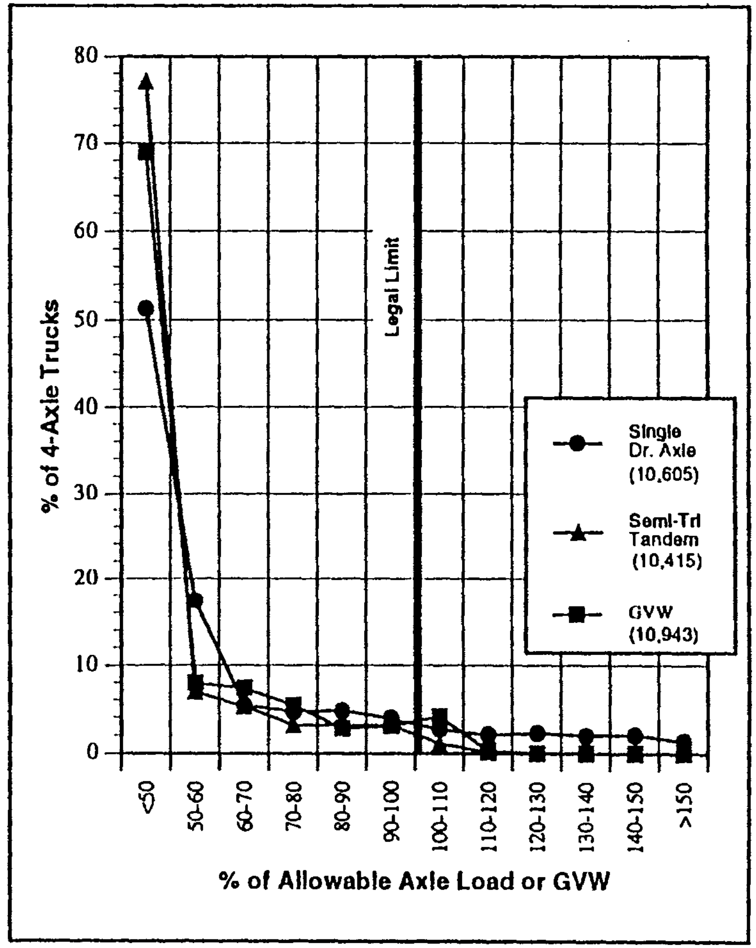


Figure 5.6 Four-axle Truck Loads: Weekday Aggregate Profile, 6 June – 15 July 1994.

The most common configuration of 4-axle trucks (95% of this class) is the 2-axle tractor pulling a tandem-axled semitrailer. The drive (single) axle on the tractor is particularly suspect for overloading since the tandem-axled semitrailers are ordinarily pulled by 3-axle tractors on the long haul. Drayage companies, however, often use older 2-axle tractors unfit for long-hauls to shuttle these semitrailers back and forth across the border over relatively short distances. Approximately 10% of the single drive axles on 4-axle trucks exceed legal limits by at least 10% (Fig 5.6). The aggregate drive-axle load profile for 4-axle trucks is shown in Figure 5.8. As seen from this figure, the modal loading for this axle is from 3,640 to 4,550 kg (35.6 to 44.5 kN) (8 to 10 kips); roughly 14% of these axles exceed the allowable 20-kip limit. Between 1 and 2% of these drive axles exceed the allowable limit by more than 50%.

Five-axle tractor-semitrailer combinations are the dominant vehicle conducting transborder hauling at this port-of-entry. They constitute roughly 97% of all 5-axle trucks and 60% of all trucks with respect to all classes combined. One might suspect that a significant percentage of these trucks are overweight, but this is not the case at the Laredo port-of-entry. Less than 2% exceeded the GVW limit by more than 10%. Less than 3% of drive-tandems and semitrailer-tandems exceeded load limits by more than 10% (Fig 5.9). Aggregate axle-load profiles for both tandem sets are shown in Figures 5.11 and 5.12; GVW profiles are shown in Figure 5.13. As can be seen in Figures 5.11 through 5.13, loading of 5-axle trucks appears to be bi-modal, representing groups at the empty and nearly full extremes.

As a group, 6-axle tractor-semitrailer combinations are the only axle-count class which is consistently grossly overweight. Their dubious notoriety is somewhat mitigated by the fact that they constitute only 2% of the observed truck population. Over the period of analysis, drive tandems, tridems, and GVWs belonging to 45-50% of these vehicles were more than 10% above the legal limit (Fig 5.10). Equally impressive is the fact that 10-15% of the observations in these load or weight categories exceeded limits by more than 50%! Aggregate load profiles are shown in Figures 5.14 through 5.16.

5.4 RELATIVE DAMAGE AND TRUCK FACTORS

The ESAL concept and the equations resulting from the AASHO Road Test are described in Chapter 3. Because ESALs are dependent on pavement type, thickness or structural number, and terminal serviceability parameters, some assumptions were necessary prior to an assessment of damage due to observed truck traffic. For purposes of this study, analysis focused strictly on flexible pavements with a structural number ($\overline{SN}$) of 5 and terminal serviceability (P_t) of 2.5. These assumptions were made with the view that asphalt concrete pavements are the dominant type and these parameters are fairly typical of high-type pavements constituting the majority of the long-haul network in Texas.

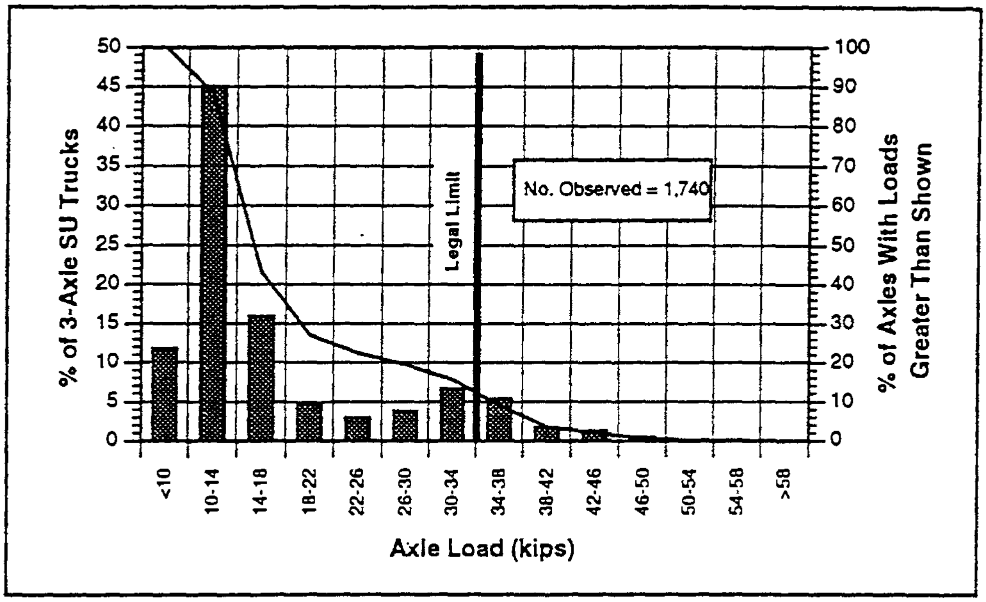


Figure 5.7 Axle Loads (Drive Tandem), 3-Axle SU Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

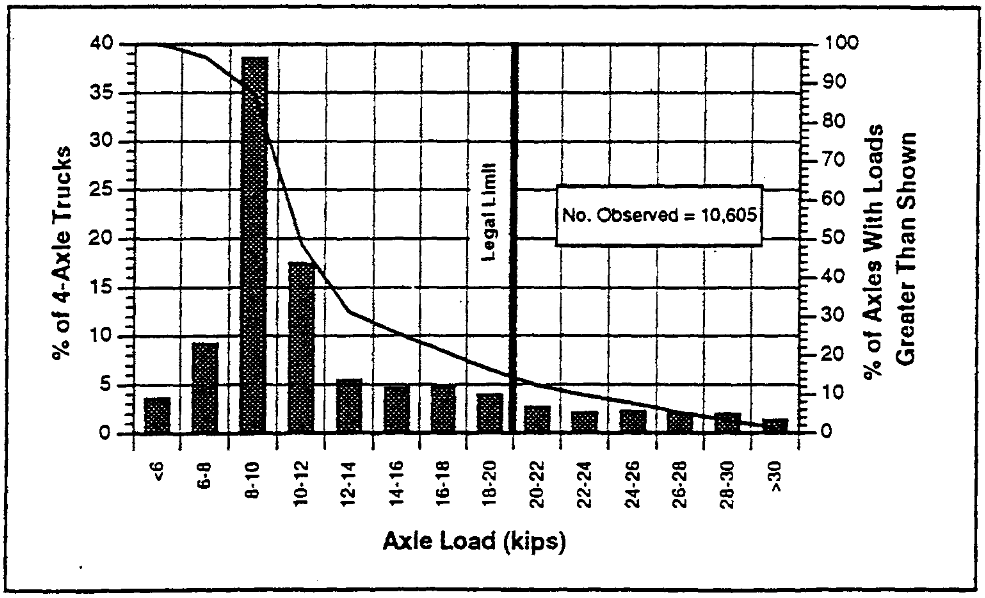


Figure 5.8 Axle Loads (Drive Axle), 4-Axle SU Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

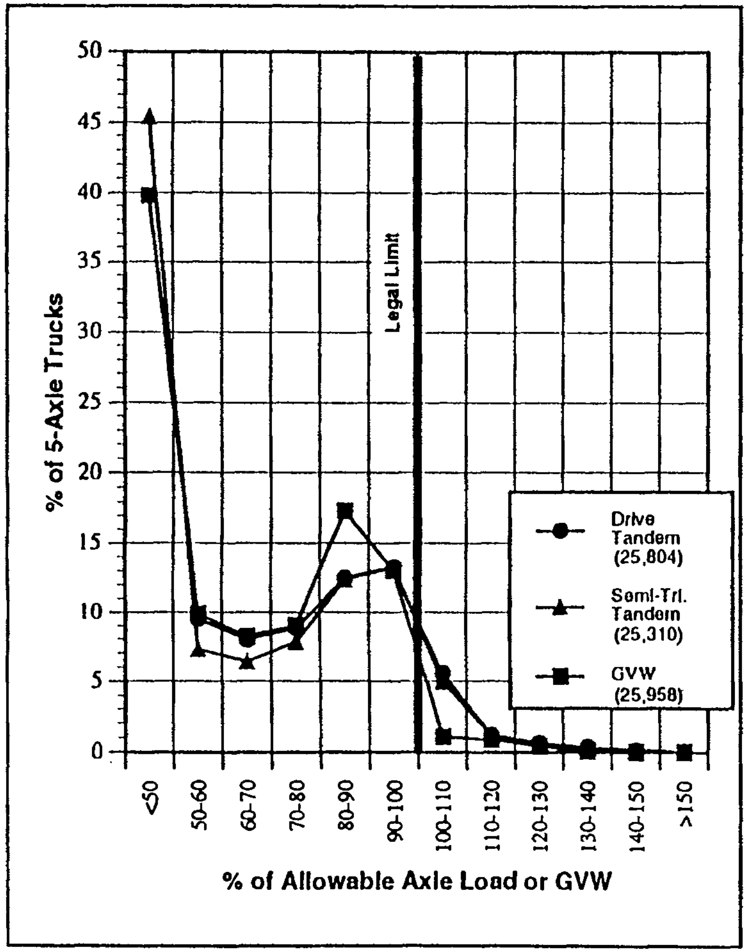


Figure 5.9 Five-Axle Truck Loads: Weekday Aggregate Profile, 6 June – 15 July 1994

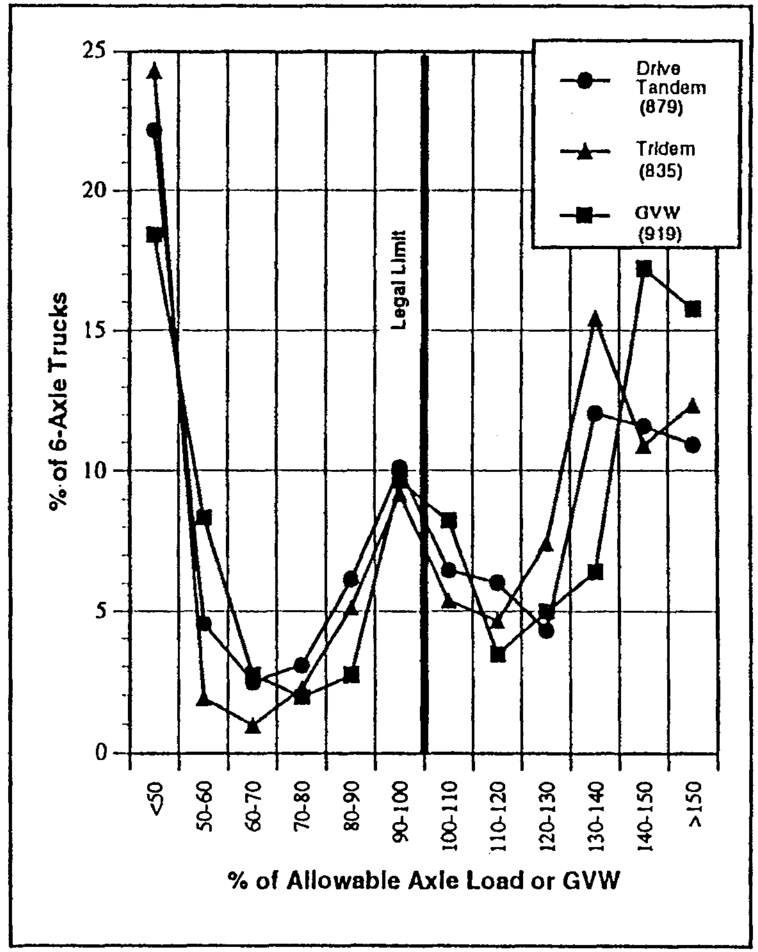


Figure 5.10 Six-Axle Truck Loads: Weekday Aggregate Profile, 6 June – 15 July 1994

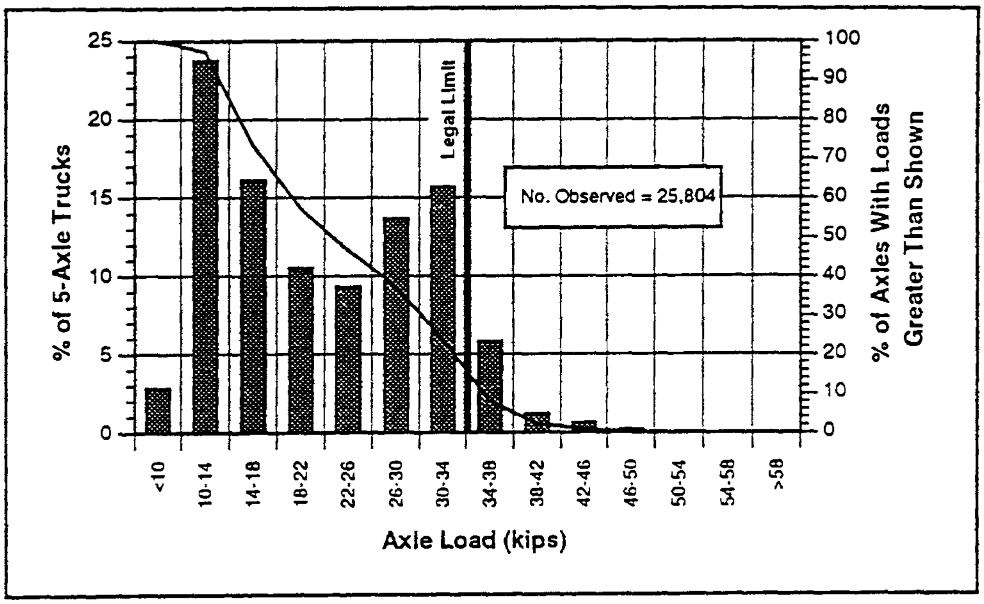


Figure 5.11 Axle Loads (Drive Tandem), 5-Axle Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

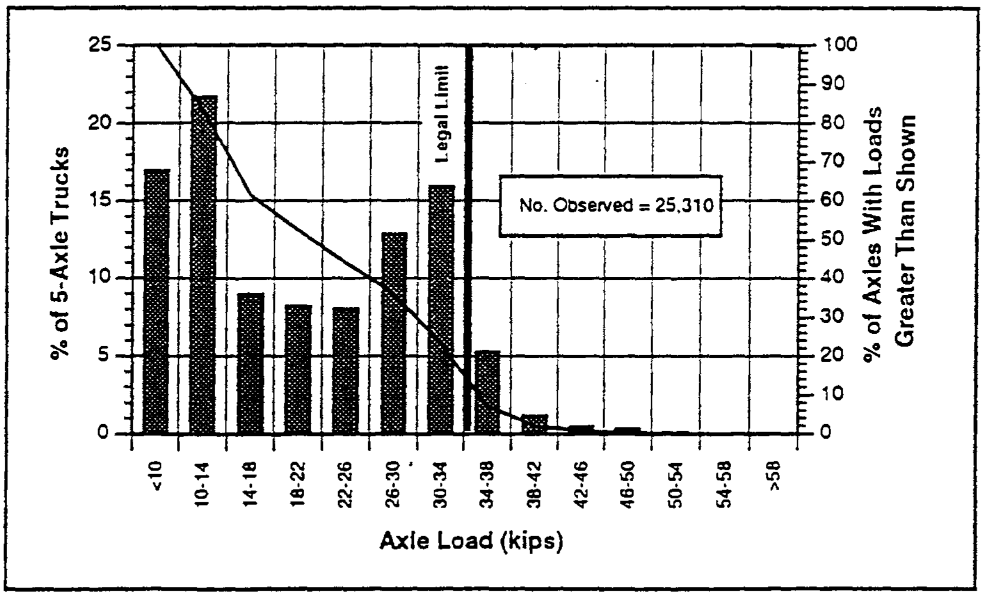


Figure 5.12 Axle Loads (Semi-Trl. Tandem), 5-Axle Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

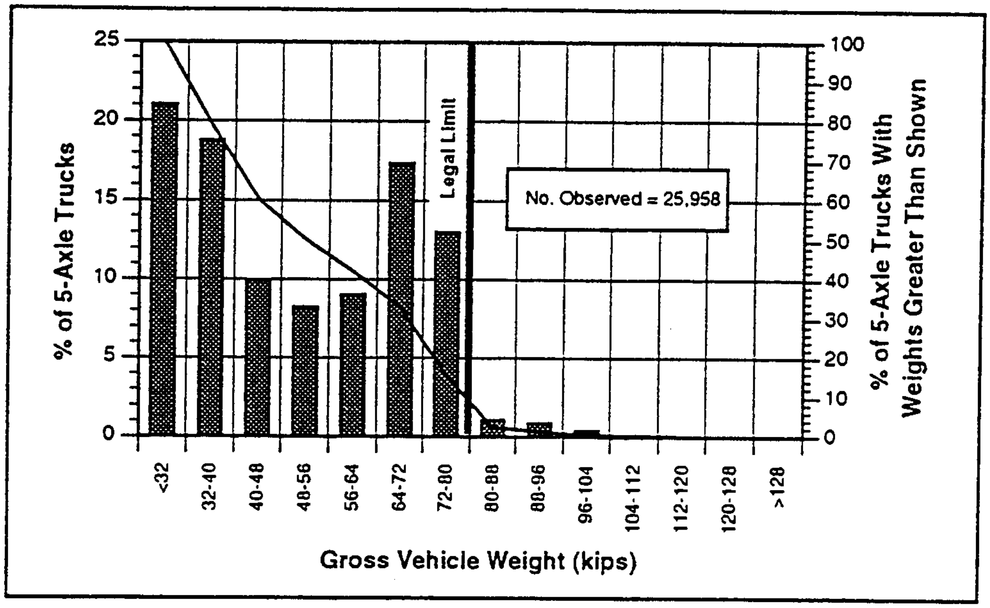


Figure 5.13 Gross Vehicle Weights, 5-Axle Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

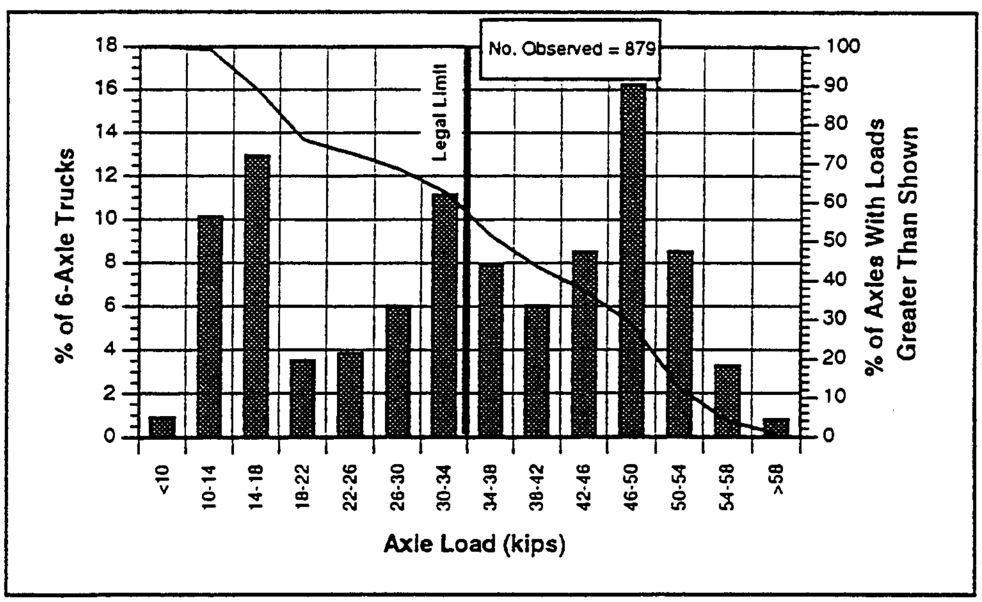


Figure 5.14 Axle Loads (Drive Tandem), 6-Axle Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

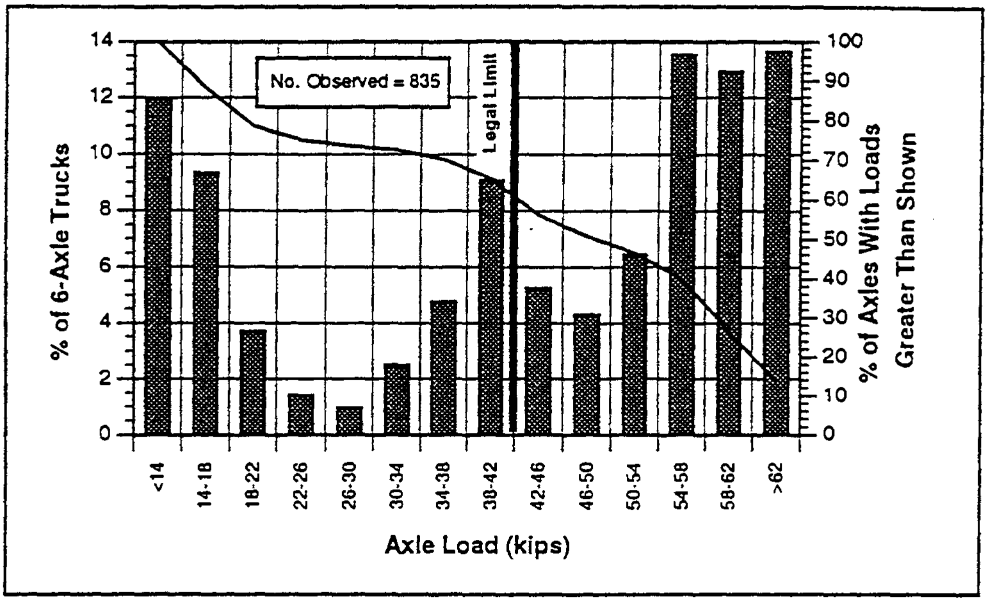


Figure 5.15 Axle Loads (Semi-Trl. Tridem), 6-Axle Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

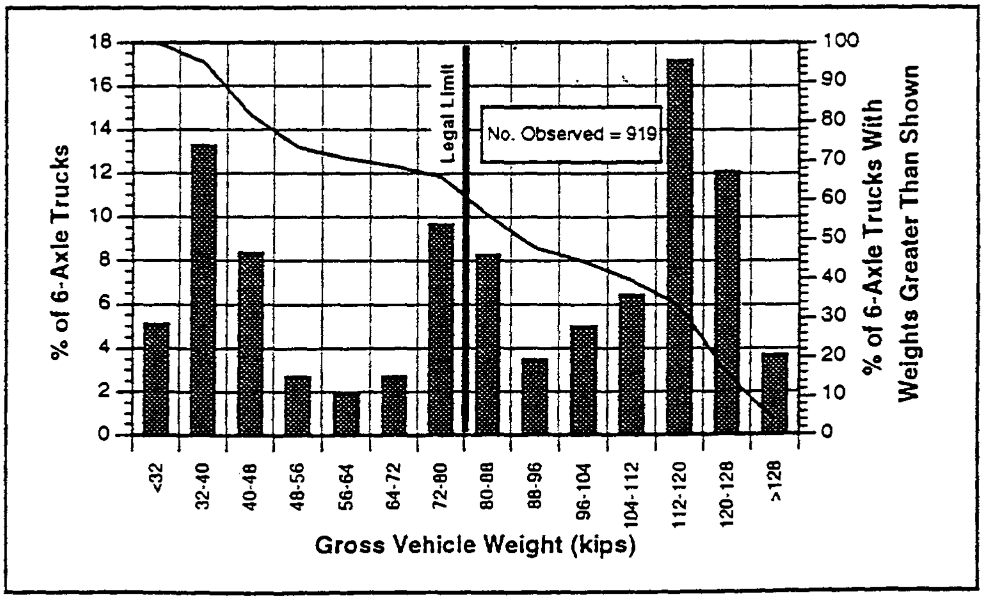
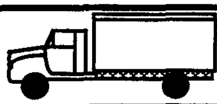
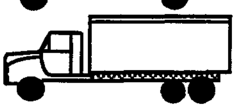
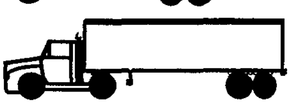
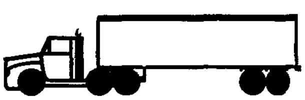
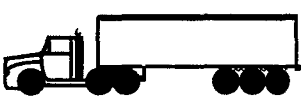


Figure 5.16 Gross Vehicle Weights, 6-Axle Trucks: Weekday Aggregate Profile, 6 June – 15 July 1994

ESALs were then assessed in each type of axle group for each basic class of truck. Dividing these totals by the total truck counts by class enables the calculation of an "ESAL factor" summary statistic, or the average number of ESALs per truck by class. Preliminary division of truck records into empty and loaded categories gives an appreciation for the relative damage caused by trucks carrying at least a partial load against that caused by empty trucks, and the relative damage of one category of trucks against another. The daily distribution of truck classes together with their loads is summarized in Table 5.2. From this table, it can be seen that trucks which are at least partially loaded constitute about 80% of the total truck population, while they generate almost 99% of the damage. During weekdays, loaded 5-axle trucks comprise just under 50% of the entire population and contribute slightly more than 60% of the total damage. Because of their extreme overloading, 6-axle vehicles contribute over 9% of the damage although they constitute slightly less than 2% of the total population.

*Table 5.2. Daily Distribution of Loaded Trucks**

Axle Count	Predominant Configuration	Average Daily Count	Percent of Total Count	Average Daily ESALs	Percent of Total ESALs	ESAL Factor
2		57 (12)	3.8 (2.7)	12 (6)	1.1 (2.0)	.21 (.50)
3		58 (15)	3.9 (3.3)	22 (6)	2.0 (2.0)	.38 (.40)
4		324 (107)	21.5 (23.4)	277 (110)	25.6 (36.1)	.85 (1.03)
5		732 (222)	48.5 (48.6)	655 (175)	60.6 (57.8)	.89 (.79)
6		28 (1)	1.8 (0.3)	102 (1)	9.4 (0.4)	3.64 (1.00)
	Total	1199 (357)	79.5 (78.3)	1068 (299)	98.7 (98.3)	

* Saturday figures in parenthesis.

Weekly variations in ESAL factors are shown in Figures 5.17a and b. Note the high variability in 6-axle loads on weekdays and for most truck classes on Saturdays. Populations of 2-, 3-, and particularly 6-axle trucks are small on Saturdays, which makes statistical generalization for these categories less meaningful.

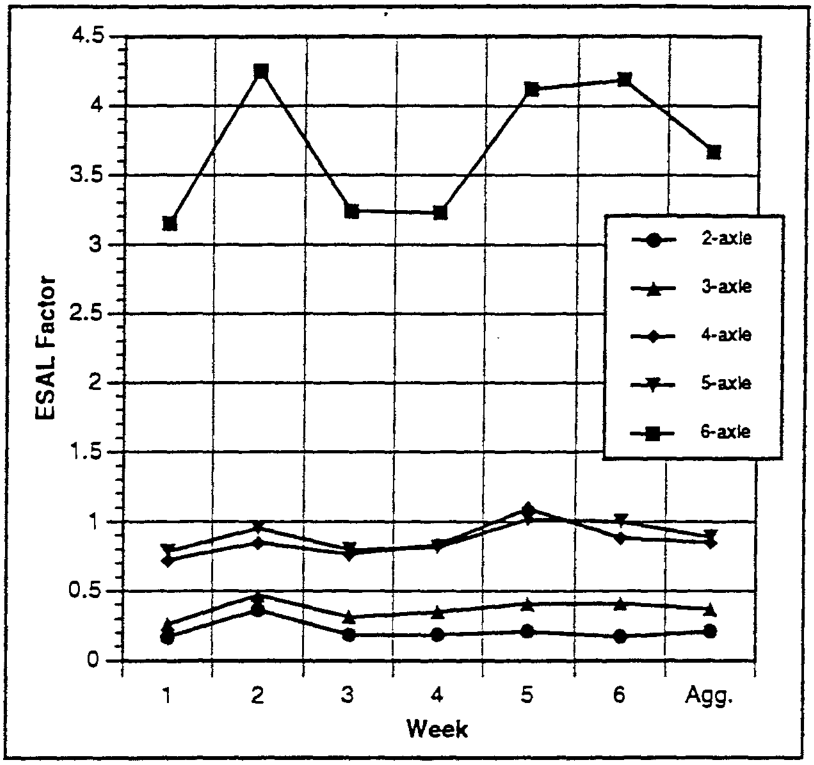


Figure 5.17a Weekly Variations in Weekday ESAL Factors

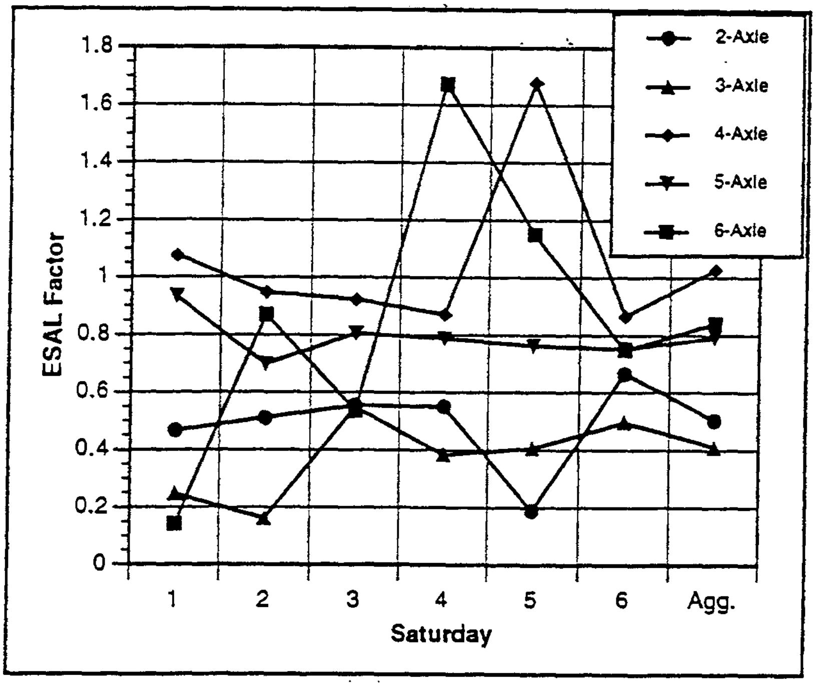


Figure 5.17b Weekly Variations in Saturday ESAL Factors

A comparison of ESAL factors derived from the Laredo site during the analysis period against a two-day inventory of over 6,500 truck records collected by a 4-lane WIM system located on I-35 south of San Antonio provides insight into relative damage between corresponding truck classes operating in the respective areas. The differences are summarized in Table 5.3.

Table 5.3 Comparison of Northbound (Laredo) Transborder Commercial ESAL Factors to I-35 ESAL Factors

Configuration (axle count)	(a) I-35 ESAL Factor	(b) Laredo ESAL Factor	% Difference (Col. b to a)
2	.27	.21	- 22
3	.26	.38	46
4	.46	.85	85
5	.83	.89	7
6	.66	3.64	451

Note that, except for the 2-axle class, all truck classes representative of the Laredo site have higher ESAL factors than corresponding truck classes operating at the I-35 site. Little difference exists between respective 5-axle populations, the dominant truck class at both sites. The typical 6-axle truck from the Laredo site would cause approximately four and one-half times the damage to a selected pavement as a 6-axle truck typical of the I-35 site.

5.5 DATA IRREGULARITIES

As mentioned earlier in this chapter, improper lane tracking and software settings prevented the collection and proper classification of a substantial portion of the truck traffic processed at the study site prior to June 1994. Additionally, files which were generated contained irregular records on the order of 20% of the daily count, calling into question the level of confidence which could be placed in the remaining usable files as being representative of the total truck population processed through this port-of-entry. As will be shown, correcting the lane tracking and software problems also had a dramatic effect on reducing irregular records.

5.5.1 Correction of Site Shortcomings

The original site plan called for edge and centerline pavement stripes to assist truck drivers in proper lane tracking. Delays in scheduling prevented application of the stripes prior to mid-November 1993. Once they were applied, no significant decrease in the proportion of erroneous files (or increase in the number of legitimate records) was observed. Follow-up visits to the site to conduct direct data download revealed that these pavement markings were quickly becoming obliterated by traffic and dust conditions at the site. A follow-up application of directional arrows and "no-parking" signs along the north edge of the pavement was accomplished in late February 1994. Raised pavement marker buttons epoxied to the centerline and edge stripping were to be applied during the same time frame, but delays with scheduling again occurred.

In mid-March, physical surveillance of the site over a six-hour period was conducted in an attempt to better correlate the volume of erroneous records with the cause. Videotaping was performed to assist in the post-analysis. The surveillance revealed that about 20% of trucks failed to use the lane properly. Improper use consisted of intentionally straddling the centerline or driving completely in the on-coming traffic lane, or failing to remain centered in the lane in order to pass trucks which parked on the shoulder for short periods of time (5-15 minutes). This site monitoring made it clear that button markings would have little impact on encouraging truck drivers to stay within the proper lane; a recommendation was made to install vertical lane delineators to encourage proper lane usage. The City of Laredo agreed to order and install these devices, which, after administrative and weather delays, was accomplished on May 18, 1994.

On June 1, 1994, while a PAT technician was in the process of calibrating a similar WIM system near the Zaragosa bridge in El Paso, it was determined that certain parameters governing the presence indication of slower moving combination vehicles had to be changed from their default settings to properly record these trucks. Corresponding settings at the Laredo site were adjusted by telemetry on June 2, 1994.

The effects of these corrective measures can be gleaned through comparison of values in Tables 5.4 and 5.5, then through subsequent comparison of data shown in Tables 5.5 and 5.2. Table 5.4 contains a summary of weekday data spanning the period 28 February - 25 March 1994, prior to the installation of the vertical lane delineators or changes to software parameters. This summary is representative of Phase 1, prior to any corrective measures being implemented. Table 5.5 contains a summary of weekday data spanning the period 19 May - 1 June 1994, prior to the adjustment of software parameters, and will be referred to as Phase 2. As noted earlier, Table 5.2 contains a summary of weekday data from 6 June - 15 July, after both corrective actions were taken, and will be referred to as Phase 3.

In the first comparison between Phases 1 and 2, the most notable aspect of adding lane delineators is the largely anticipated increase in the overall number of records collected. This trend is present for all truck classes except 6-axle combinations. Also notable is that the proportion of 3-axle trucks to the total count increased by 40% and the ESAL factor for 2-axle trucks increased by 28%; these two events will be further addressed below.

There are many striking changes in comparing summaries of data from Phases 2 and 3, but all are directly linked. The inability to properly record slower-moving combination vehicles (4- and 5-axle tractor-semitrailer rigs) was partially responsible for increasing the counts of 2- and 3-axle trucks during Phase 2. Slower-moving combinations would be inadvertently "split" into two vehicles with the tractor constituting the first and the semitrailer constituting a closely-following second vehicle. This process was not confined to a narrow speed range, but rather to any speed up to 20 mph. An algorithm incorporated into the sorting program placed the semitrailer portion into an error file since no 2-axle vehicles are configured with the small axle spacings of tandem axle groups. This process left the 2- and 3-axle tractors, often carrying loads, to be registered as 2- or 3-axle single-unit trucks. Since many were hauling a load, the ESAL factor for the overall 2- and 3-axle classes was artificially raised. Once the software corrections were made, dramatically decreasing the frequency of split records, the number of 2- and 3-axle records decreased (along with their ESAL factors), the 4- and 5-axle records increased, and the overall number of records decreased.

Table 5.4. Daily Distribution of Loaded Trucks: Phase 1

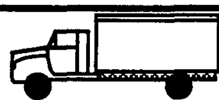
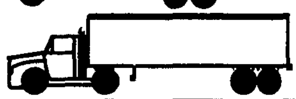
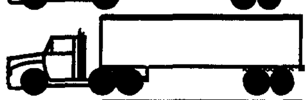
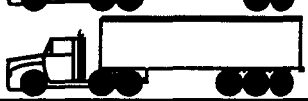
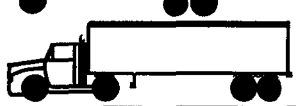
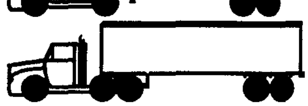
Axle Count	Predominant Configuration	Average Daily Count	Percent of Total Count	Average Daily ESALs	Percent of Total ESALs	ESAL Factor
2		75	7.2	47	5.6	.63
3		92	8.8	49	5.8	.54
4		198	18.9	163	19.1	.82
5		442	42.2	439	51.6	.99
6		30	2.9	143	16.8	4.70
	Total	837	79.9	841	98.9	

Table 5.5. Daily Distribution of Loaded Trucks: Phase 2

Axle Count	Predominant Configuration	Average Daily Count	Percent of Total Count	Average Daily ESALs	Percent of Total ESALs	ESAL Factor
2		155	9.7	126	9.8	.81
3		197	12.4	110	8.6	.56
4		273	17.1	234	18.3	.86
5		676	42.3	656	51.5	.97
6		29	1.8	138	10.8	4.69
	Total	1331	83.3	1264	99.0	

5.5.2 Error Files

The majority of error files were also a direct consequence of the previously mentioned shortcomings. Improper lane usage caused the generation of records with "zero" wheel loads. Manifestations of software problems included the generation of records containing 11-axle vehicle configurations, a highly improbable configuration for this site. Other records contained vehicles with improbable axle spacings and loads. Some contained vehicles with high speeds, where site constraints are known to prevent truck speeds greater than 40 mph. Correcting the lane tracking problem alone reduced the volume of error records as a percentage of the total number of records from 20% to about 13% of the total. When this correction was combined with software adjustments, the percentage of error files dropped to no more than 5%. However, while most categories of error decreased, the adjustments made to software parameters occasionally produce their own unique error records. Two closely spaced trucks are sometimes "read" as a single vehicle, combining their axle counts and loads into a single truck record. These errors are tolerable (less than 2% of the total error) considering the much greater number of error reductions generated through the same procedure.

CHAPTER 6. DAMAGE IMPLICATIONS

In the previous chapter, loading traits were summarized for each of five basic truck classes processed into the U.S. through the Laredo port-of-entry. With the exception of trucks in the 6-axle class, trucks within a given class generally comply with U.S. load limits. The ESAL factor for rigs in the 5-axle class crossing into the U.S. was only 7% above that for the same class operating on Interstate 35 just south of San Antonio. For commercial motor carriers, the 5-axle class format is the most popular in both Mexico and the U.S., and will probably constitute the workhorse for the bulk of long-haul highway trade for many years to come. Mexican tractors which deliver semitrailers to U.S. carrier yards in the commercial zone may be generally in compliance with U.S. load limit standards for reasons of expediency in handing off trailers, avoiding additional delays required to transload cargo before the U.S. truck is allowed to leave the carrier yard. However, once interborder transport restrictions are repealed in the bordering states under NAFTA, the current cargo transfer procedures will gradually be eliminated, and Mexican carriers will be allowed access to virtually the entire Texas highway system. The outcome of harmonization talks addressing commercial carrier size and weight regulations remains to be seen; even if the U.S. refuses to compromise on the weight issue "officially," enforcement of load limits may continue to be lax. With this in mind, the following discussions will also include comparisons involving results of a 1991 truck weight survey conducted in Mexico (Ref 20).

6.1 PROJECTION OF DESIGN ESALS

One method which can be used as a basis to determine the net effect of changes in individual truck factors to the overall service life of a highway facility is to examine the percent change in projected ESAL accumulations over a specified period under varying compositions of traffic. The worksheet method outlined in Appendix D of the *AASHTO Guide for Design of Pavement Structures* (Ref 31) was used to determine the design ESALs for existing traffic, which was then used as a basis for comparison against hypothetical traffic stream mixes composed of U.S. and Mexican carriers. Traffic streams which include percentages of commercial truck traffic typical of the population exiting the Laredo customs yard, and typical of the population involved in the 1991 Mexican truck weight study, are both explored. In addition, by using a spectrum of annual traffic growth rates, an assessment is made on the relative importance of growth rates to increases in ESALs over the analysis period, versus increases due only to traffic streams with higher average ESAL factors.

In this investigation, an analysis period of 20 years is used throughout. Design ESALs generated by three levels of Mexican-origin truck traffic (10%, 20%, and 30% of the total truck stream) are compared against a 100% U.S.-origin stream which is typified by traffic sampled at the aforementioned Interstate 35 site. Appropriately weighted ESAL factors are used for the mixed traffic. A constant growth rate of 3% for 2- and 3-axle trucks is used throughout since some growth can be expected, but will probably be less than the more dominant tractor-semitrailer rigs used in most commercial long-haul trade. Growth rates of 5, 8, and 10% are used for 4-, 5-, and 6-axle trucks. Table 6.1 is a summary of design ESALs generated by these traffic compositions. Predicted ESALs based on traffic loadings measured in the 1991 Mexican truck weight survey — making U.S. trucks behave like Mexican trucks — are shown in parentheses.

Table 6.1 Design ESALs[1] (Millions) for Traffic Streams Composed of U.S. and Mexican Origin Commercial Trucks

Traffic Split (U.S./Mex.)	Annual Growth Rate[2]			% Above Current ESALs[3]
	5%	8%	10%	
100/0 (existing)	20.1	27.5	34.2	——
90/10	20.4 (21.9)	27.9 (30.1)	34.7 (37.4)	1.4 (9.3)
80/20	20.6 (23.8)	28.3 (32.6)	35.2 (40.6)	2.8 (18.5)
70/30	20.9 (25.7)	28.7 (35.1)	35.7 (43.7)	4.2 (27.8)

[1] 20 year analysis period used.
[2] 3% growth assumed for 2- and 3-axle truck classes throughout.
[3] Within a given growth rate.

From Table 6.1 it can be seen that a 1.4% increase in ESALs is realized over a 20-year analysis period, with each 10% increase in the proportion of Mexican trucks typical of the Laredo mix introduced into the existing traffic stream. Similarly, if the proportion of Mexican trucks introduced into the traffic stream is composed of trucks typical of the 1991 Mexican truck weight study, for each 10% increase in the proportion of these trucks, a greater than 9% increase in ESALs is realized. By comparing AASHTO traffic growth factors over the 20-year analysis period, for each 2% increase in the projected growth rate, approximately a 24% increase in ESALs is realized. Growth in ESALs due to increases in annual growth rates can also be appreciated by comparing adjacent columns in Table 6.1. The Mexican dimension is substantial. When U.S. trucks are loaded to Mexican weights identified by IMT, it produces over a six-fold increase in predicted ESALs.

6.2 PAVEMENT DAMAGE

At the end of Chapter 2, infrastructure management concerns addressed the problem of premature highway wear-out when high volumes of heavily laden trucks, not anticipated during design stages, are operated over the system. This in turn will require early expenditure of resources to maintain a desired level of serviceability and safety.

For pavements, a rough estimate of the reduction in service life can be made by comparing the design ESALs for the original design load against those projected to accumulate under increased loads or growth rates. For example, the AASHTO process used above might be performed on a hypothetical base traffic stream mix resulting in 20×10^6 ESALs as the design load over a 20-year analysis period. A subsequent traffic mix projection might entail the accumulation of 22×10^6 ESALs over the same period. Since the road was originally designed to withstand only 20×10^6 ESALs, a reduction in life is expected. The original estimate of ESAL accumulations is 9.1% lower; a corresponding reduction in the AASHTO growth factor is required to make the projected traffic "fit" the original design. The AASHTO growth factor equation is

$$\text{Growth Factor } (G_F) = \left[(1+g)^n - 1\right]/g \text{ ,}$$

where

$$g = \frac{growth\ rate}{100} \text{ for non-zero growth rates, and}$$

$$n = \text{the analysis period.}$$

By solving for n, a new analysis period, n' corresponding to the reduced growth factor, G_F', is established.

$$n' = \frac{ln\left[g(G_F')+1\right]}{ln(1+g)},$$

where the growth rate can also be varied to correspond to the new traffic stream mix. Here, n' may be viewed as the analysis period corresponding to the shortened pavement life caused by increasing traffic volume and loading. As an example, consider data from Table 6.1. If the existing traffic mix from the Interstate 35 WIM site is used with an assumed 5% rate of growth as a base case ($G_F = 33.1$), 20.1×10^6 ESALs will accumulate during the 20-year analysis period. If the projected traffic will consist of an 80/20 split (U.S. to Mexican origin), with an 8% growth rate, 28.3×10^6 ESALs will accumulate. To accumulate the same quantity of overall ESALs of the base case, a 29% reduction in the original growth factor must be applied to the new traffic mix. This new growth factor, G_F', is equal to 23.5. Solving the above equation for n' and using the projected 8% growth rate gives an analysis period of 13.7 years, reflecting the decrease in expected pavement life. Table 6.2 shows a sampling of n' corresponding to design ESALs in Table 6.1, as compared against the base case of existing traffic with an assumed 5% growth rate over a 20-year analysis period. As before, quantities shown in parentheses apply to trucks surveyed in the 1991 Mexican truck weight study. Again, it is apparent that misjudging projected traffic growth rates decreases pavement life more than do increases in average truck weight. However, since the impact of Mexican 6-axle trucks is not captured in this analysis, the weight impacts are probably undervalued.

Table 6.2 Analysis Period (n′) (years) Resulting From Increase in Design ESALs While Maintaining Basic Pavement Design

Traffic Split (U.S./Mex.)	Annual Growth Rate		
	5%	8%	10%
100/0 (existing)	20.0*	14.0	11.3
90/10	19.8 (18.9)	13.9 (13.2)	11.2 (10.7)
80/20	19.7 (17.9)	13.7 (12.6)	11.1 (10.2)
70/30	19.5 (17.0)	13.6 (12.0)	11.0 (9.7)

*Basis of Comparison

A pavement cost model, such as the one developed by Deacon (Ref 40) and appearing in truck weight studies which have grappled with the issue of improving freight-hauling efficiency without increasing road wear (Refs 14, 19), generalized costs for pavement rehabilitation for changes in projected cumulative traffic loadings measured in ESALs. For purposes of the model, pavement rehabilitation is defined as "application of substantial asphalt concrete overlays" (Ref 14). Both variable and fixed costs are accounted for, where variable costs are essentially a function of the quantities of materials used, and fixed costs include such items as placing leveling courses, repairing joints, improving drainage, and controlling traffic. The model is based on the AASHTO pavement design and performance equations and takes into consideration pavement type, thickness, and design and environmental parameters. Remaining pavement life of an existing pavement is calculated, followed by the annualized cost of all future resurfacing work under a known base traffic mix and under a 10% increase in base traffic loading. A discount factor of 7% was used to convert all rehabilitation costs to uniform annual costs. The additional cost in rehabilitation is then the difference between the annualized rehabilitation costs for the base loading case and the case which entails a 10% increase in loading. Resurfacing intervals were standardized for both cases and set equal to that used in the base case.

A sensitivity analysis conducted on Deacon's cost model showed that the added costs for pavement rehabilitation associated with the 10% increase in loading varied little from pavement to pavement, with soil resilient modulus (M_R) being the main contributor. For a 10% increase in ESALs on flexible pavement, the added rehabilitation costs ranged between $5.9 per meter-km ($12 per foot-mile) (M_R = 77,570 kPa or 11,250 psi) and $9.8 per meter-km ($20 per foot-mile)

(M_R = 8,620 kPa or 1,250 psi). For rigid pavements, added rehabilitation costs ranged from $7 to $26 under the same soil conditions. For simplicity in expressing results, a value of $7.9 meter-km ($16 per foot-mile) for both pavement types was then assumed. The generalized cost in dollars, *X*, for the actual percentage increase in loading, *Y*, can be expressed as $X = 16(Y/10)$. Using this relationship, and the base case cited for Table 6.2, an estimate of the increased costs for rehabilitating existing pavements due to hypothetical mixes of U.S. and Mexican commercial truck traffic can be made. These results are given in Table 6.3, with quantities in parentheses based on the 1991 Mexican truck weight survey values for 5-axle semitrailer trucks..

Table 6.3 Increases in Rehabilitation Costs for Increased Traffic Loading ($/ft.-mi.)

Traffic Split (U.S./Mex.)	Annual Growth Rate		
	5%	8%	10%
100/0 (existing)	0	58.90	112.20
90/10	2.40 (14.30)	62.10 (79.60)	116.20 (137.70)
80/20	4.00 (29.50)	65.30 (99.50)	120.20 (163.20)
70/30	6.40 (44.60)	68.50 (119.40)	124.20 (187.90)

The cost model also estimated costs for constructing new (or reconstructed) pavements based on the new traffic loading, with the underlying premise that thicker pavements are needed to carry greater loads. From the AASHTO pavement design equations, the logarithm of design ESALs (traffic loading) was plotted against the logarithm of structural number, yielding a straight line with slope equal to 0.15. A 10% increase in traffic loadings thus yields a 1.5% increase in the pavement structural number or thickness. The added cost, *X*, for new construction above that required for the existing mix of traffic can be generalized by $X = 0.015C \times (Y/10)$, where *C* is the construction cost for a particular type of roadway (four-lane highway, interstate, etc.) in dollars per mile (1.6 km = 1 mile), and *Y* is the actual percentage increase in ESALs (Ref 14). Predicted rehabilitation costs are sensitive both to traffic growth and heavier trucks and, again, since 6-axle trucks are excluded from this analysis, the weight impacts are undervalued.

6.3 BRIDGE DAMAGE

In modeling bridging damage and associated costs caused by traffic loading, the quantity and complexity of relevant and necessary considerations are significantly greater than those for pavements. To construct a model, the span length, type (simple or continuous), and composition are all essential considerations. For the applied (truck) traffic loading, both vehicle loads and configuration (axle spacings) must be considered, as must the rare occurrences of a multiple truck presence incident which may overstress the structure. In 1992, the Federal Highway Administration (FHWA) commissioned a study into heavy truck bridge impacts, incorporating vehicle operating cost, time delays and emissions with the more usual engineering costs. This was stimulated by work done at the Center for Transportation Research, The University of Texas at Austin, which demonstrated the substantial user costs triggered by bridge rehabilitation activities and also suggested a more accurate way of identifying deficient structures (Ref 41). A computer model system was devised to take input data from the National Bridge Inventory (NBI), identify which structures were deficient for a given truck configuration and weight, calculate bridge replacement costs, together with the additional costs (sometimes viewed as external costs) identified above (Ref 1). This approach was an expanded version of that first developed in a Transportation Research Board policy report (Ref 14). The new models were not used in this report because they were not fully released, but should be evaluated in border infrastructure planning when available. Not to be overlooked are the long term environmental effects which play a role in structural deterioration (Ref 42). Because of these complexities, no analogous generalizations will be made as were made for pavements in the previous section.

6.3.1 Overstress Costs

In Chapter 3, mention was made that modern highway bridges are designed with generous safety factors which make damage through overstress improbable. Nevertheless, some states have opted to take proactive measures by increasing their design standards for new primary highway bridges to HS-25, at a cost increase of about 5% above the HS-20 standard (Ref 14). Recall that the HS-20 design standard uses a 9,090-kg (89-kN) (20 ton), 3-axle tractor-semitrailer design vehicle; the HS-25 design entails a 25% increase in the design vehicle's gross weight and individual axle loads. Since it is not cost-effective to strengthen many existing bridges, upgrading designs for new bridges often makes fiscal sense. To estimate the cost of overstress caused by a new traffic mix, existing bridges must be identified for which critical vehicles within the new mix cause the bridge operating rating (75% of the yield stress of critical members) to be exceeded by more than 5% (current standard for HS-20 bridges). Further, these bridges must not already be listed as deficient under the current traffic mix. These newly identified bridges would have to be posted with load restrictions and applicable traffic rerouted, or the bridge would have to be replaced.

6.3.2 Bridge Fatigue Costs

A study conducted for the Ohio Department of Transportation and the Federal Highway Administration (Ref 42) could be used as a basis for conducting an analysis of additional (potential) bridge fatigue damage caused by increases in the volume and loading of trade traffic in Texas. In order to assess fatigue damage, Moses proposed a standardized "fatigue vehicle," the purpose of which is analogous to the 18-kip ESAL used in assessing pavement damage. That is, fatigue effects of any vehicle can be converted into a multiple of the fatigue effects of this standardized vehicle to allow for assessment of relative fatigue damage on a common basis. This standard fatigue vehicle has the basic configuration of a tractor-semitrailer, with a gross-vehicle weight of 25,550 kg (240 kN) (54,000 lbs).

Moses then divides the bridge inventory into four length classes and two type categories (simple and continuous span). A median length, representative of each length class, is selected. The stress effects of a candidate vehicle (or vehicle class) which is to be integrated into the existing traffic mix are calculated for each representative span length and compared to the stress effects of the standard 54-kip vehicle. The ratio of stress produced by the candidate vehicle to that of the standard fatigue vehicle produces a multiplier, which, when multiplied by the 54-kip standardized vehicle weight, provides a "fatigue equivalent weight" for the candidate vehicle class. Moses further develops the model for generalization purposes across all bridge categories. First, each bridge class is weighted, comparing the class total length to the grand total (all classes) span length. Next, the weighted load effect of the candidate vehicle class across all bridge categories is computed, then compared against a similar weighted load effect of the standardized vehicle, to arrive at a generalized fatigue equivalent weight.

Moses offers a service life consumption formula which relies on the "third power" damage relationship (Chapter 3) applicable to steel span construction. Two assumptions are made: the bridge fatigue life is given as 50 years, and the average daily truck traffic is 2,500 per day. The formula is as follows:

$$\%\text{ of Life Consumed} = \frac{(Candidate\ Truck\ F_{wt}/54)^3}{2500\ trucks/day \times 365\ days/yr. \times 50\ yr.} \times 100,$$

where F_{wt} is the fatigue equivalent weight. The reduction in terms of years of the expected bridge life due to a new traffic mix can then logically follow. Also, with the assumption a median price per bridge, the "percent life consumed" can then be converted into a monetary cost, allowing for the cost in reduced life caused by the new traffic stream to be assessed in terms of dollars.

6.3.3 Synthesis

Infrastructure damage was examined by considering ESAL loads for pavements while examining two methods for estimating bridge impacts without conducting any analyses.

Pavement damage is shown to be sensitive both to traffic volumes and trucks weights. Although the analysis indicates that volumes are more significant than weights, this in part reflects the assumptions made under the two headings. Moving from 5% to 10% doubles truck loads while increasing the percentages of overloaded trucks by much smaller amounts results in a reduced impact. However, the consequences of adopting Mexican size and weight limits are more severe than those modeled in this chapter. Most important is the introduction of a heavy 6-axle semitrailer which is typically severely overloaded in Mexican operations. Replacing Texas 5-axle semitrailers with a mix of Mexican 5- and 6-axle semitrailers loaded to those levels identified in the 1991 Mexican study would result in substantially greater damage. Simply replacing Texas 5-axle semitrailers with Mexican units loaded to the 1991 weight study limits results in over a six-fold increase in total design ESALs, translating to a substantially shorter pavement life. Six-axle semitrailers, loaded to 1991 weight study limits, would push these figures much higher.

Bridges are sensitive to higher gross loads, particularly when carried by short doubles of the type seen in Mexico (typical loads around 155,000 lbs). The impact of these vehicles is best modeled by the suite of models currently under development for FHWA and are too complex to be addressed in this report. However, research has already shown that bridge rehabilitation costs for heavy doubles is very high and that user costs, generated by traveling through workzones on bridges, typically equal total construction costs (Ref 41).

CHAPTER 7. SUMMARY, CONCLUSION, AND RECOMMENDATIONS

The focus of this report has been an analysis of Mexican-origin truck axle loads and gross-vehicle weights for those trucks processed through the U.S. Customs yard at Laredo, Texas. Ultimately, the findings are intended to be placed in the context of the expanding U.S.-Mexico trade environment and the attendant ramifications to the Texas highway infrastructure.

7.1 SUMMARY

Trade between Mexico and the U.S. has been increasing rapidly since the liberalization of Mexican economic policies in the mid-1980s. As a consequence, the volume of interborder commercial motor carrier activity has also dramatically increased. Maquiladora industries, which have tended to consolidate in the northern regions of Mexico, are probably in large measure responsible for sizable increases in commercial truck traffic between the U.S. and Mexico.

While the increased volume in truck-born freight might be a positive indicator of welcomed economic growth, it is not without its negative consequences. Highway engineers have known for over 70 years that heavy truck loads, delivered through individual axles and wheels, rapidly consume pavements. With damage relationships developed as a result of the AASHO Road Test in the late 1950s, it is possible to quantify, relative to the loading on a standardized axle (equivalent single axle load, or ESAL), the scope of damage caused by the passage of trucks. Alarmingly, damage caused by axle loads escalates exponentially, approximately to the fourth power of the ratio of loading on similar axle-group configurations.

Increased volumes of truck traffic on Texas highways alone will translate into increased road wear. Additionally, because of the non-linear load damage relationships, there is the potential of further increases in damage through the application of heavier overall average axle loads. This later issue warrants attention, especially when ratifications of a ratified NAFTA are considered. At present, Mexican legal axle load limits exceed corresponding U.S. limits, generally by about 10 - 15%. In addition, no cap on GVW is imposed by Mexican federal law. And most importantly, all limits are flagrantly broken at will by Mexican truckers due to a total absence of enforcement. Mexican-origin commercial trucks are currently allowed to operate within U.S. commercial zones, which extend slightly beyond border municipality limits, without weight verification checks.

The capability to weigh trucks dynamically, without interrupting normal traffic flow, has dramatically increased the availability of traffic loading data to highway engineers by allowing a near-100% capture of heavy vehicle loading distributions at selected locations. As part of a Center for Transportation Research study sponsored by TxDOT (Ref 5), the importance of the load distributions of Mexican-origin commercial traffic currently entering Texas was identified. A WIM system was strategically located in the City of Laredo to record axle loads on northbound trucks prior to their dispersal onto the City's local street network. The WIM system allows for continuous monitoring of virtually all of the loaded commercial trucks which enter the U.S. through the busiest Southwestern land port-of-entry.

Analysis of recently acquired WIM data indicates that most trucks processed through the primary Laredo port-of-entry are in compliance with U.S. legal load limits. The outstanding exception are 6-axle combinations, with as many as 50% of these vehicles exceeding allowable axle loads and GVW. Ten to 15% of this vehicle class exceeded aforementioned limits by more than 50%. However, these trucks comprise only 2% of the total observed truck population.

In an assessment of potential damage to the Texas highway system, it is worth considering that harmonization proceedings will probably allow heavier load limits on U.S. roads once interborder motor carrier restrictions are lifted. As a starting point, average Mexican truck loading may more closely resemble the distribution recorded in a 1991 truck weight study conducted in Mexico (Ref 20).

Varying the traffic stream composition by national origin and anticipated growth rates allows for the projection of design ESALs necessary in designing pavements appropriate to carry anticipated loads. Increasing the percentage of Mexican-origin commercial truck traffic representative of that currently crossing into the U.S. at Laredo and that representative of the 1991 Mexican study by 10%, results in an increase in design ESALs of approximately 1.4% and 9.3%, respectively, within a given estimated overall annual rate of growth. Design ESALs are more sensitive to the overall growth rate; increasing the annual growth rate by just 2% increases the design ESALs by more than 20% over a 20-year analysis period. However, Mexican 6-axle semitrailers would also increase the weight impact in a substantial, but unknown, amount.

Analyzing the impact of various traffic stream mixes on Texas' highway bridges is substantially more involved than corresponding assessments made on pavements. Considerations involving the bridge span length, composition, and type (simple or continuous), and both truck loads and axle spacings, must all be addressed before damage assessments can be rendered. Bridges susceptible to overstress under new traffic mixes should be either posted with load limitations or replaced. A method developed by Moses (Ref 42) for analyzing fatigue damage in bridges using a standardized "fatigue vehicle" is analogous to the process of using the ESAL in assessing relative damage to pavements. By assuming a bridge fatigue life and daily truck traffic volumes, it is possible to determine the reduction in service life caused by a heavier traffic mix over that which currently traverses any given bridge. Finally, bridge reconstruction and user cost impacts should be measured using the new suite of models developed in Texas for the FHWA (Ref 1).

7.2 CONCLUSION AND RECOMMENDATIONS

The following issues are salient to this report.

(a) U.S.-Mexico trade-related commercial truck traffic volumes are likely to continue their sizable growth rates, even while current transborder travel restrictions are in place. An accurate forecast of the commercial motor carrier growth rate is essential in allowing highway planners to develop meaningful damage projections. While increases in average axle loads are an important consideration for pavement damage, miscalculating traffic growth rates will have a far greater relative impact on pavement life.

(b) The magnitude of heavier vehicle loads, and their configurations, are particularly salient considerations in determining bridge overstress, where understanding the impact of a single "critical load" vehicle, or a multiple presence incident, are essential to ensuring that resulting moments do not exceed a bridge's operating stress.

(c) Additional study of potential damage to Texas bridges, caused by the integration of Mexican-origin heavy truck traffic into the overall Texas traffic population, should be made. Realistic traffic growth rate projections are needed to analyze fatigue costs, as well as a "critical load" vehicle(s) identified to assess overstress costs.

(d) Over $2 billion is currently projected as the minimum cost to upgrade just the border region highways in Texas (Ref 9). Realistic growth rate forecasts are needed so that this money can be spent wisely, which includes developing highway designs commensurate with the volume and actual load distribution of projected traffic. Life-cycle costs are considerably lower for incremental increases in new pavement thicknesses and greater bridge structural capacity than they are for the prospect of accelerated maintenance schedules or premature bridge replacement on inadequately designed facilities.

(e) To minimize widespread degradation of Texas highway serviceability, designation of special "trade routes" should be explored. Already, officials in counties bordering on Interstate 35 (Ref 43) are pushing for federal designation of a NAFTA "superhighway" in hopes of obtaining additional federal funding for anticipated upgrades. A similar designation may be appropriate for segments of Interstates 10 and 45 and for U.S. Highways 59, 77, and 281.

(f) WIM systems provide a rapid and effective method to screen potential load limit violators. Whether harmonization talks result in the U.S. retaining its lower legal load limits, or in raising load limits, WIM systems should be placed in the vicinity of each highway port-of-entry to screen for overweight violators. If designated "trade routes" are established, WIM systems could be used at major interchanges to screen traffic for violators traveling unauthorized routes. All WIM-system data should be recorded and analyzed continuously to establish trends in traffic loading at every site.

(g) Weight enforcement policy should be strict, with penalties based on sound cost-recovery principles such as assessing damage attributable by equivalent fatigue weight (Ref 42) for bridge cost recovery and ESAL-miles (1.61 km = 1 mile) for pavement cost-recovery.

(h) Border communities are already feeling the impact of increased traffic volumes and loads within the limits of their commercial zones. More effective cost-recovery practices should begin here. In particular, the cost-recovery studies performed by

Said (Ref 8), combined with the loading distribution findings in this report, could be examined by Laredo officials to revise their current bridge toll strategy and develop a more equitable fee schedule.

(i) Collection and interpretation of data from the Laredo WIM site should continue with the objective of analyzing trends not covered in this report. Specifically, long-term and seasonal changes in commercial truck composition, volumes, and loading distribution should be monitored. Comparisons should also be made with data recorded at the Zaragosa site in El Paso, which was commissioned in June 1994.

(j) Northbound truck and trailer movements at Laredo are broadly in compliance (6-axle semitrailers being the exception) with Texas weight laws. This is interesting given the severe overloading seen in Continental Mexico. Explanations range from shippers reducing loads during the study to trucks moving at other points of entry. After many discussions with operators, the authors take another position. The measurements are accurate and reflect true traffic flows. Most moves are accomplished through partnerships and U.S. truckers and railroads will not accept overloaded trailers. The question then is to what extent changes in the legislation on operations around December 17, 1995 will affect these partnerships and encourage Mexican truckers to operate deep within Texas. Without strict weight enforcement such a development is likely to lead to accelerated infrastructure wear and higher rehabilitation costs.

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APPENDIX A

Laredo WIM System Calibration Data

Calibration Data, 6 October 1993: 3-Axle Single-Unit (FHWA Type 6) Calibration Truck

Assumed Static Loads and Weights (kips) (some averaging of static scale loads used):

Steering Axle: 6.87

Axle #2: 17.69

Axle #3: 17.44

Tandem Group: 35.13

GVW: 42.00

Table A.1a Axle Loads and GVWs of Calibration Truck (kips), 6 October 1993

Pass No.	Steering Axle	Axle #2	Axle #3	Tandem Group	GVW
1	6.6	18.2	17.7	35.9	42.5
2	7.0	16.6	16.7	33.3	40.3
3	6.8	19.8	15.7	35.5	42.3
4	6.8	18.7	18.9	37.6	44.4
5	7.0	16.4	17.5	33.9	40.9
6	6.1	17.3	16.7	34.0	40.1

Table A.1b Statistical Analysis of Calibration Truck Axle Loads and GVWs (kips), 6 October 1993

	Steering Axle	Axle #2	Axle #3	Tandem Group	GVW
Range:	0.9	3.4	3.2	4.3	4.3
Min.	6.1	16.4	15.7	33.3	40.1
Max.	7.0	19.8	18.9	37.6	44.4
Mean	6.72	17.83	17.20	35.03	41.75
Standard Deviation	0.34	1.31	1.09	1.61	1.64
Variance	0.11	1.72	1.20	2.58	2.69

Calibration Data, 9 December 1993: 4-Axle Tractor-Semitrailer (FHWA Type 8) Calibration Truck

Assumed Static Loads and Weights (kips) (some averaging of static scale loads used):

Steering Axle: 6.20

Drive Axle: 13.00

Semi-Trl. Tandem: 17.84

GVW: 37.32

Table A.2a Axle Loads and GVWs of Calibration Truck (kips), 9 December 1993

Pass No.	Steering Axle	Tractor Drive Axle	Semi-Trl. Tandem	GVW
1	6.0	13.0	16.8	35.8
2	6.2	12.7	18.6	37.5
3	6.7	12.4	17.1	36.2
4	5.8	13.4	17	36.2
5	5.9	13.2	16.8	35.9
6	6.0	13.0	17.2	36.2
7	6.0	13.0	17.6	36.6
8	6.0	13.2	17.4	36.6
9	6.3	13.0	18.0	37.3
10	6.1	13.3	17.2	36.6
11	6.4	13.5	18.4	38.3
12	6.1	13.1	18.4	37.6
13	5.9	13.3	18.4	37.6
14	6.6	12.5	18.0	37.1
15	6.3	12.1	17.5	35.9
16	6.2	13.0	18.0	37.2
17	6.6	12.1	18.3	37.0
18	5.9	13.2	18.1	37.2
19	6.2	13.0	18.5	37.7
20	6.2	13.7	17.2	37.1
21	6.1	13.3	17.7	37.1

Table A.2b Statistical Analysis of Calibration Truck Axle Loads and GVWs (kips), 9 December 1993

	Steering Axle	Tractor Drive Axle	Semi-Trl. Tandem	GVW
Range:	0.9	1.6	1.8	2.5
Min.	5.8	12.1	16.8	35.8
Max.	6.7	13.7	18.6	38.3
Mean	6.17	13.00	17.72	36.89
Standard Deviation	0.25	0.43	0.59	0.68
Variance	0.06	0.18	0.35	0.47

APPENDIX B:

Biweekly Trends in Axle Loads and Gross-Vehicle Weights

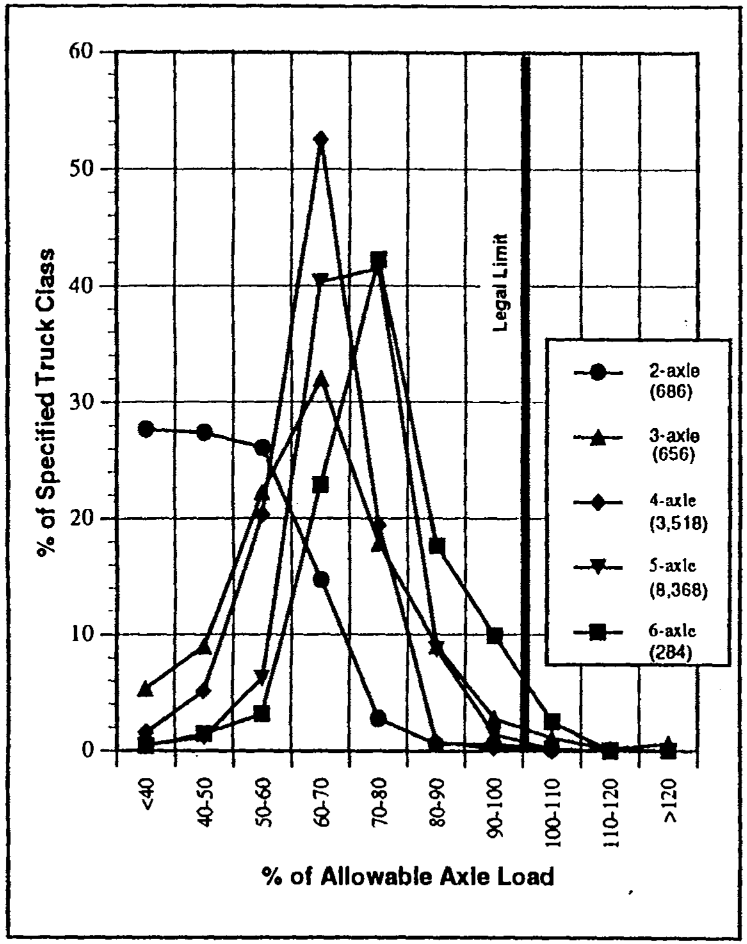

Figure B.1 Steering-Axle Loads: Weekday Profile, 6 - 17 June 1994

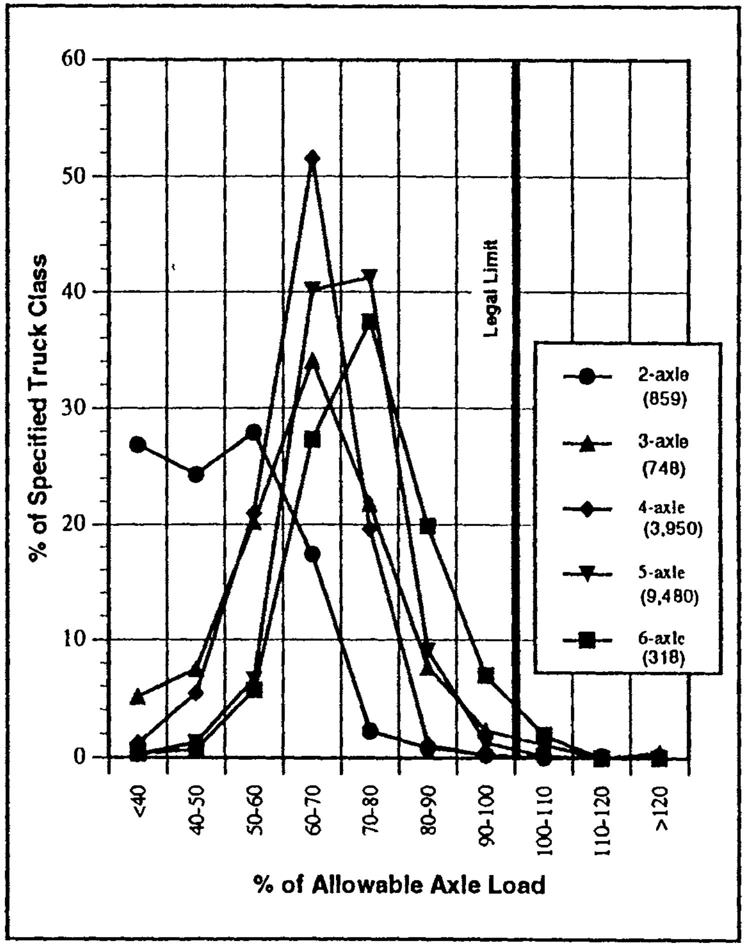

Figure B.2 Steering-Axle Loads: Weekday Profile, 20 June - 1 July 1994

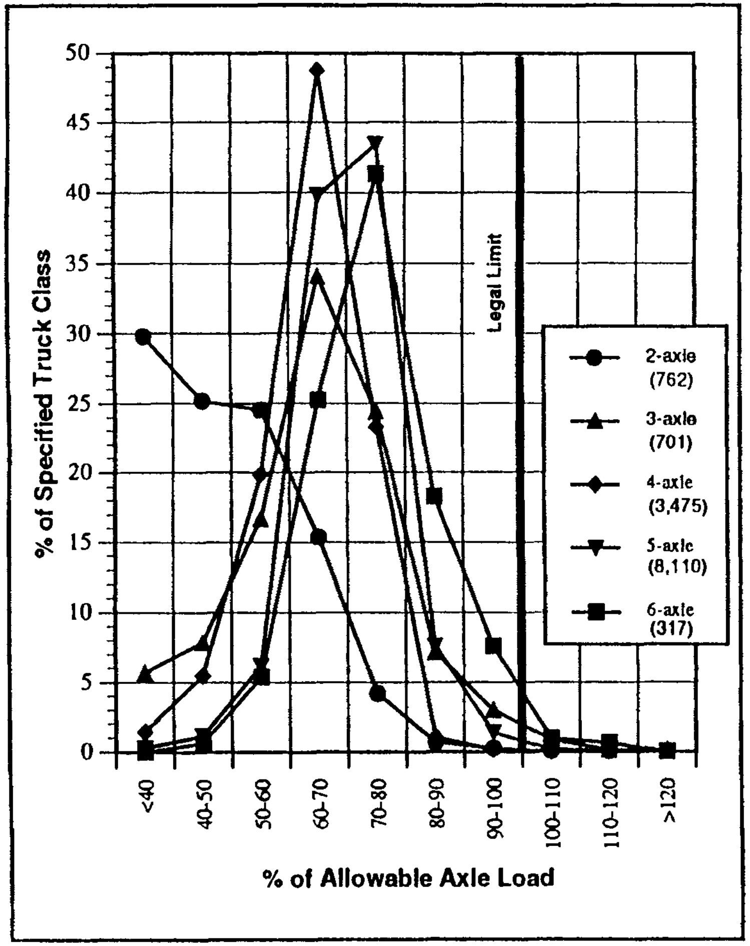

Figure B.3 Steering-Axle Loads: Weekday Profile, 5 - 15 July 1994

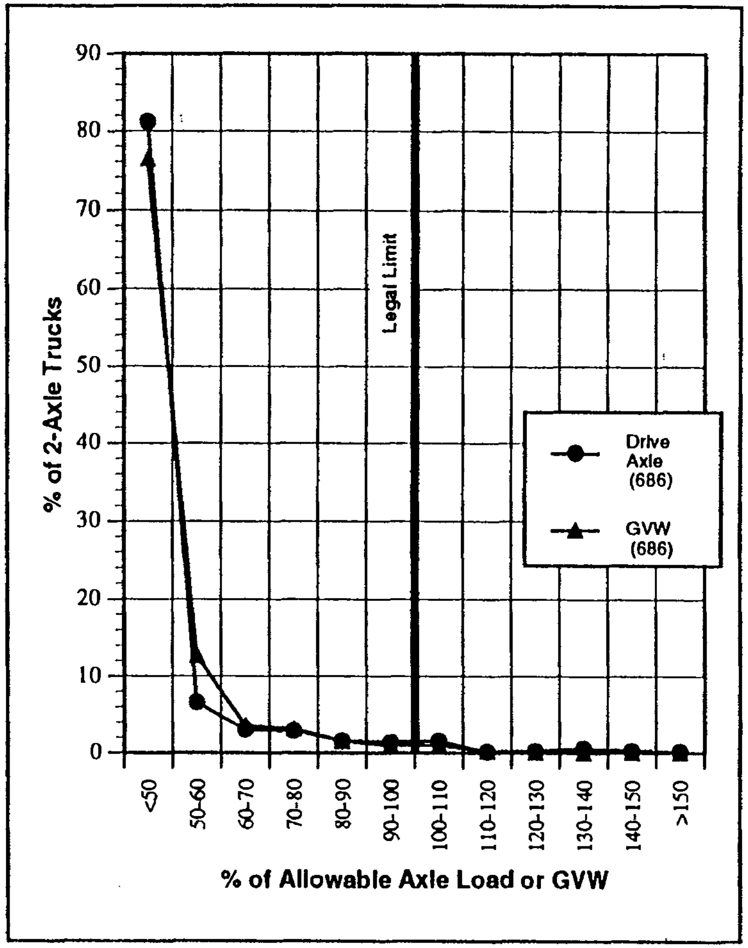

Figure B.4 2-Axle Truck Loads: Weekday Profile, 6 - 17 June 1994

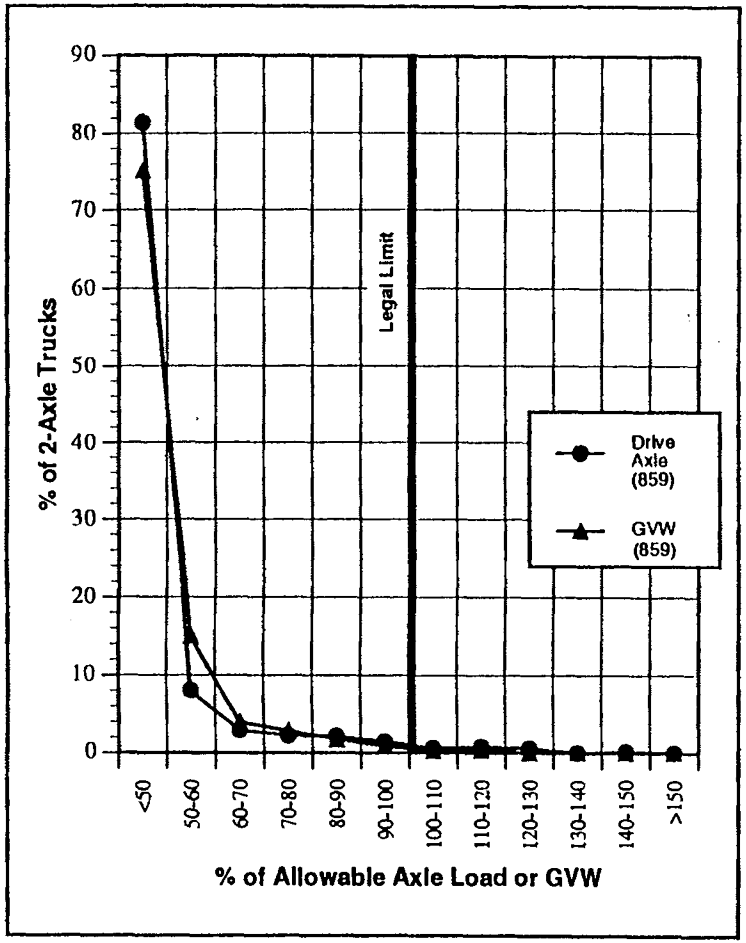

Figure B.5 2-Axle Truck Loads: Weekday Profile, 20 June - 1 July 1994

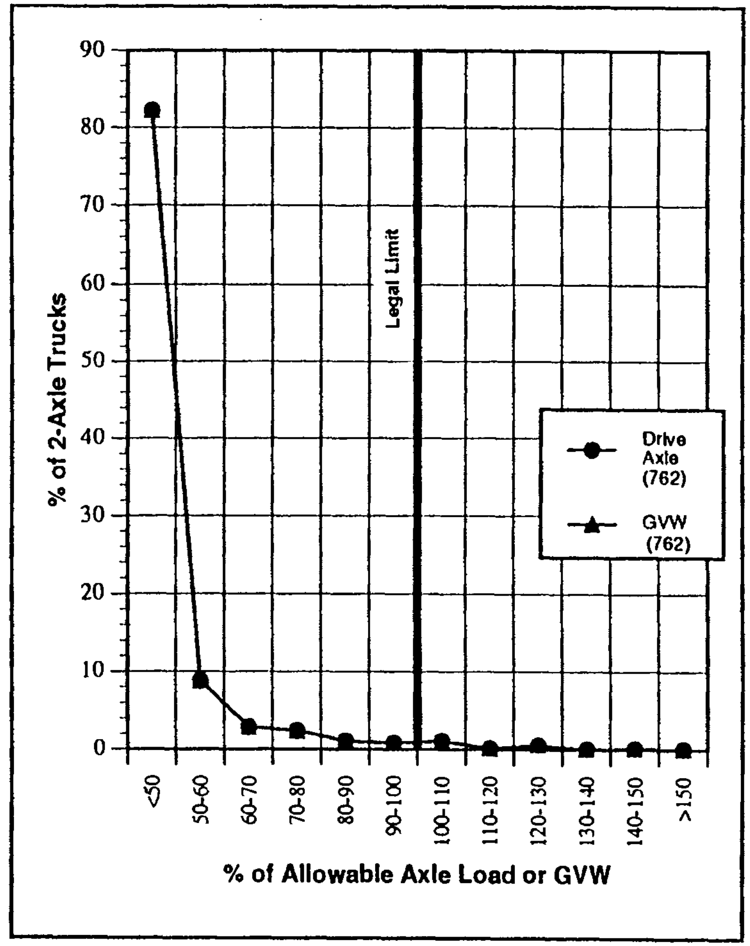

Figure B.6 2-Axle Truck Loads: Weekday Profile, 5 - 15 July 1994

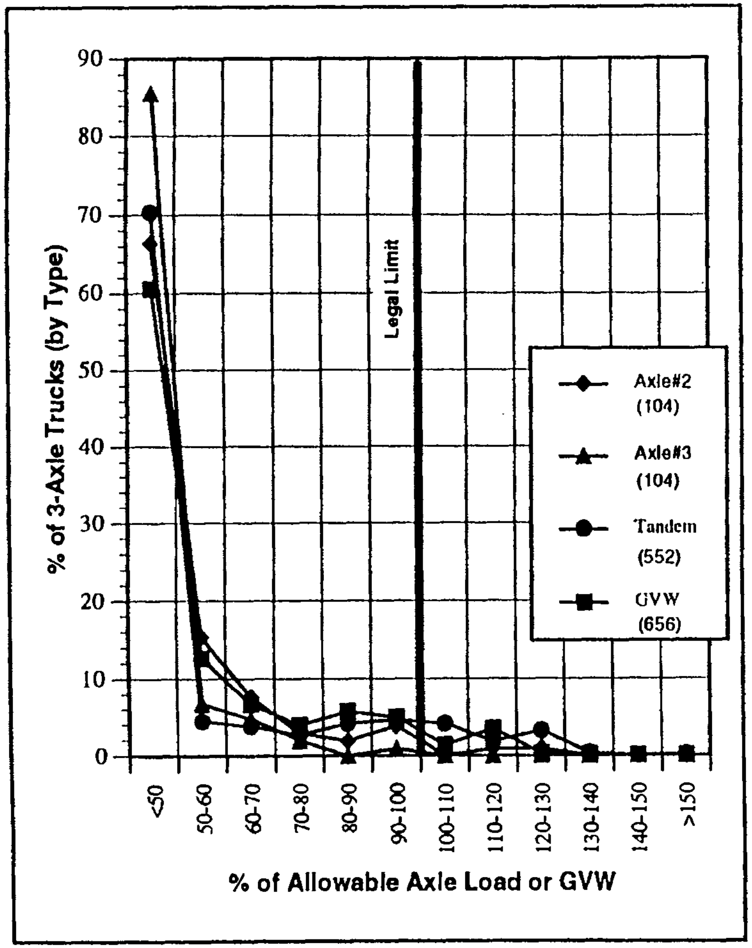

Figure B.7 3-Axle Truck Loads: Weekday Profile, 6 - 17 June 1994

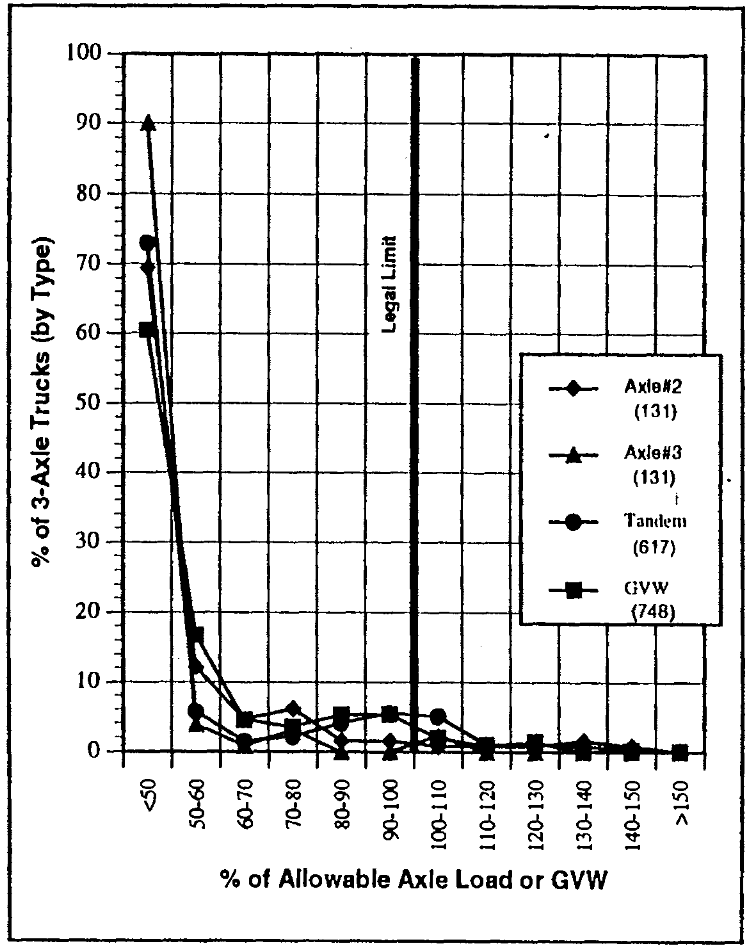

Figure B.8 3-Axle Truck Loads: Weekday Profile, 20 June - 1 July 1994

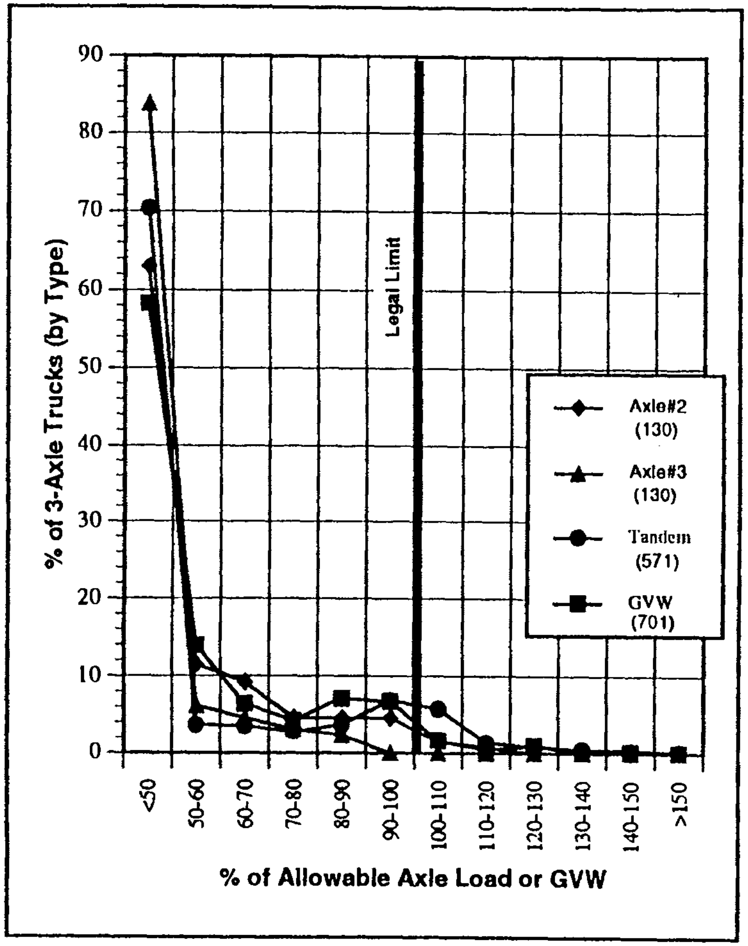

Figure B.9 3-Axle Truck Loads: Weekday Profile, 5 - 15 July 1994

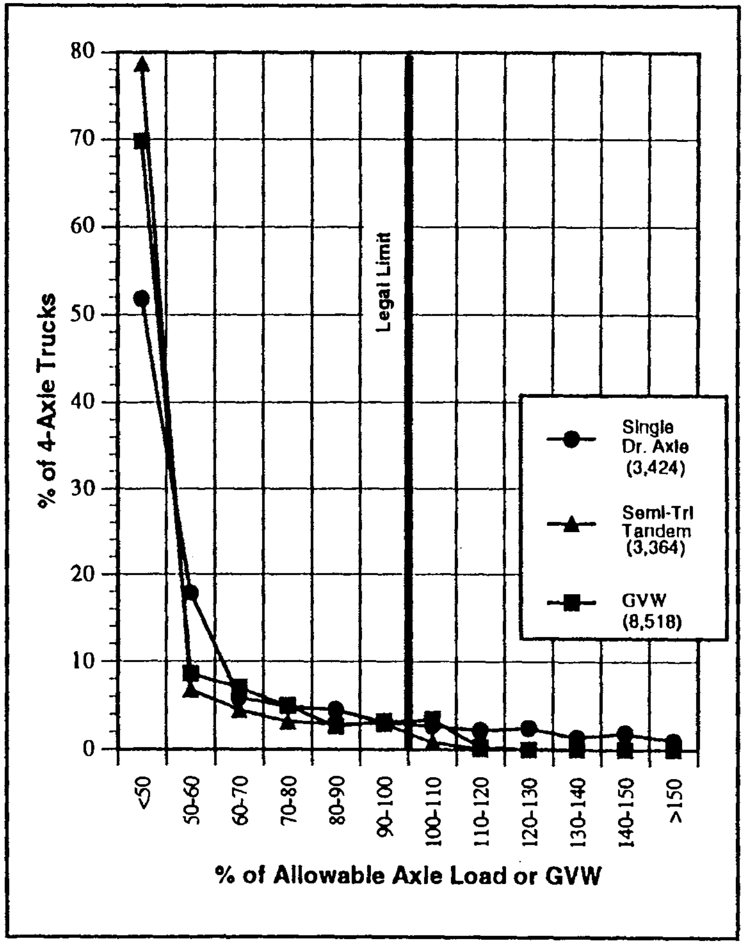

Figure B.10 4-Axle Truck Loads: Weekday Profile, 6 - 17 June 1994

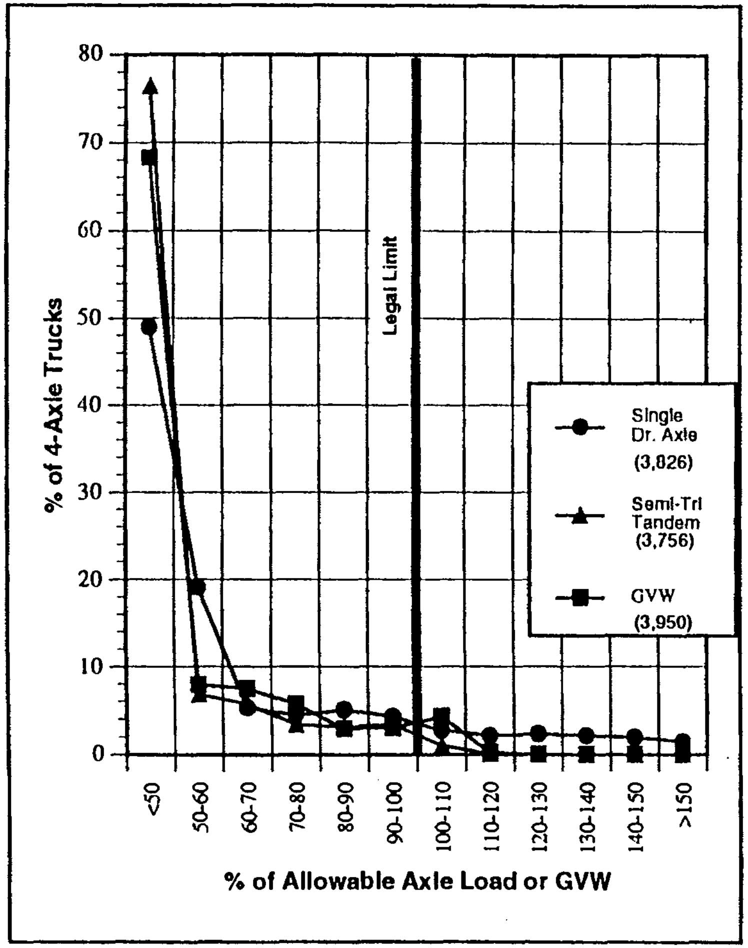

Figure B.11 4-Axle Truck Loads: Weekday Profile, 20 June - 1 July 1994

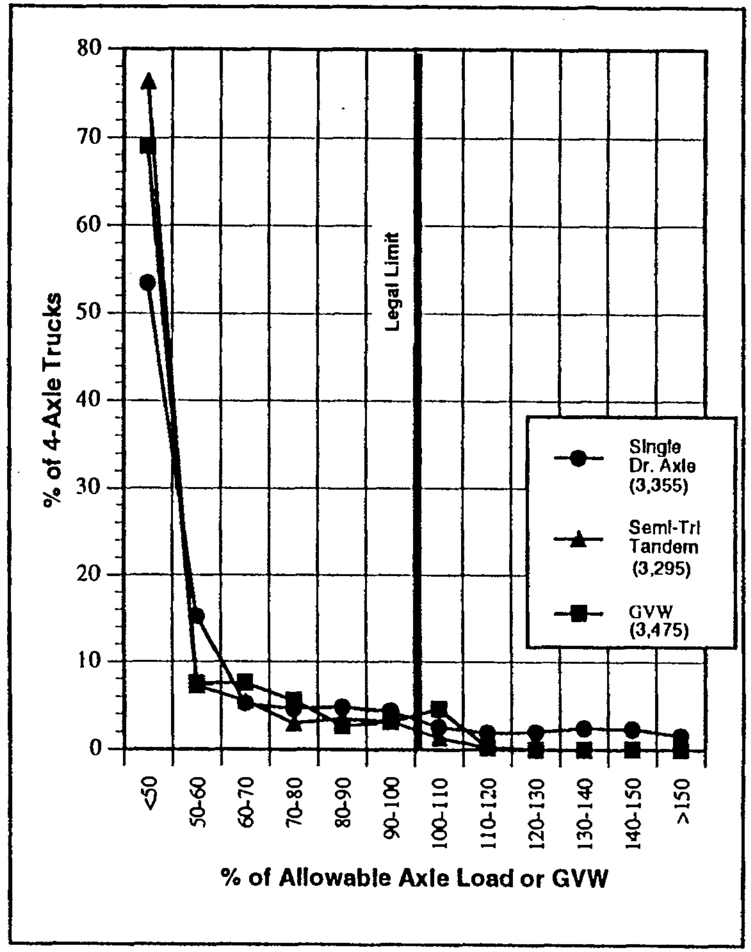

Figure B.12 4-Axle Truck Loads: Weekday Profile, 5 - 15 July 1994

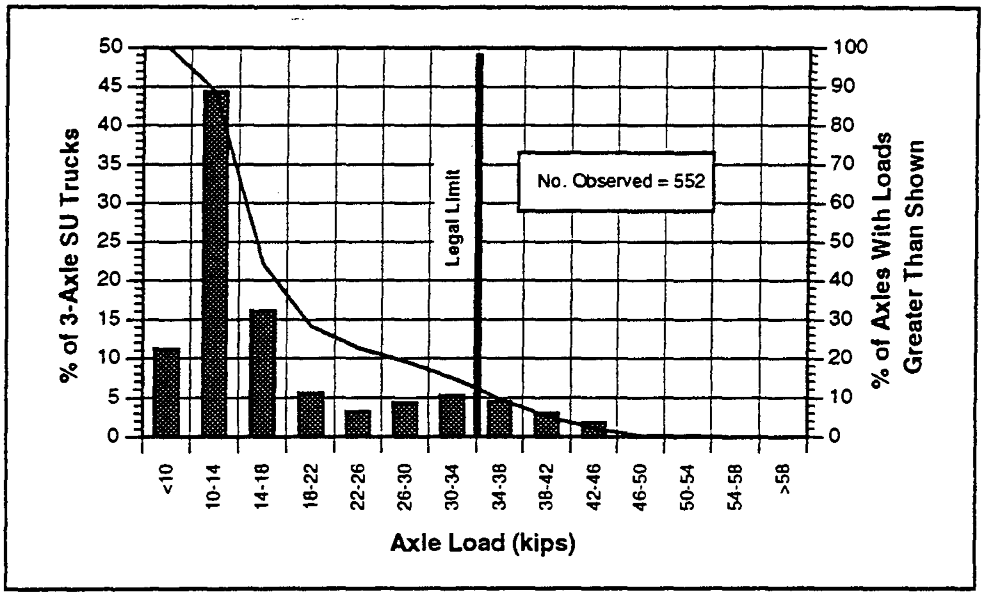

Figure B.13 Axle Loads (Drive Tandem), 3-Axle SU Trucks: Weekday Profile, 6 - 17 June 1994

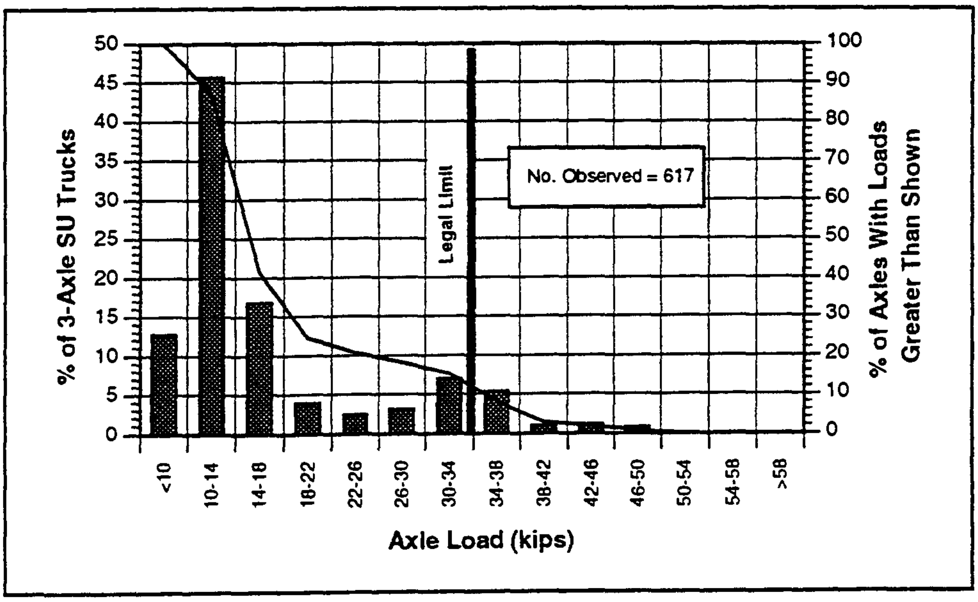

Figure B.14 Axle Loads (Drive Tandem), 3-Axle SU Trucks: Weekday Profile, 20 June - 1 July 1994

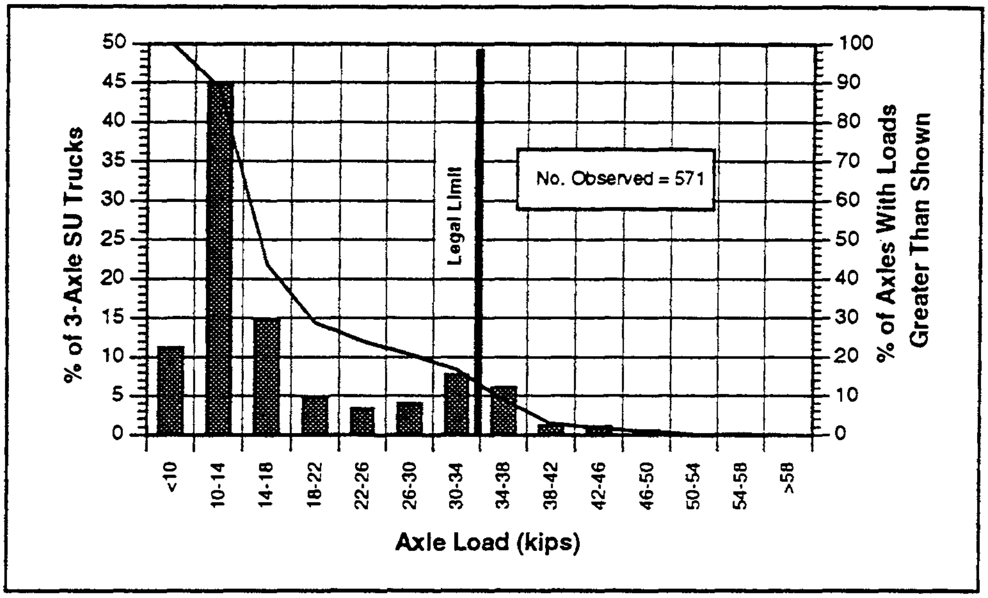

Figure B.15 Axle Loads (Drive Tandem), 3-Axle SU Trucks: Weekday Profile, 5 - 15 July 1994

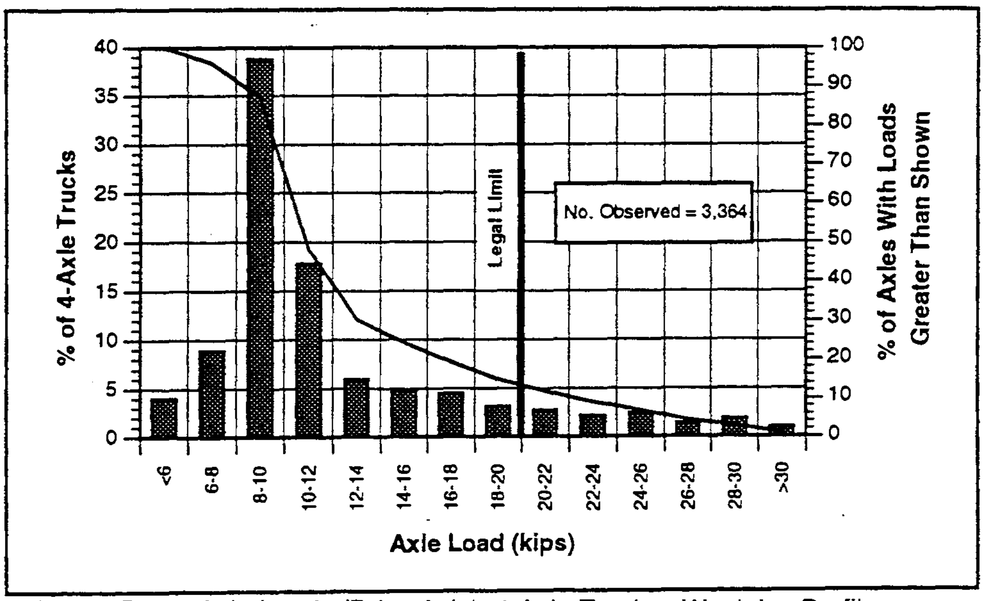

Figure B.16 Axle Loads (Drive Axle), 4-Axle Trucks: Weekday Profile, 6 - 17 June 1994

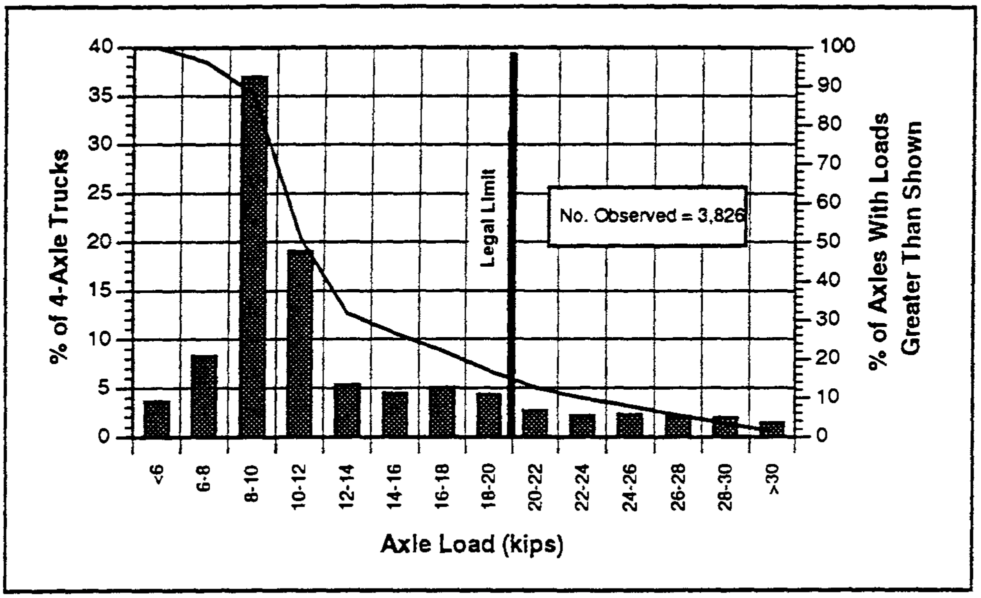

Figure B.17 Axle Loads (Drive Axle), 4-Axle Trucks: Weekday Profile, 20 June - 1 July 1994

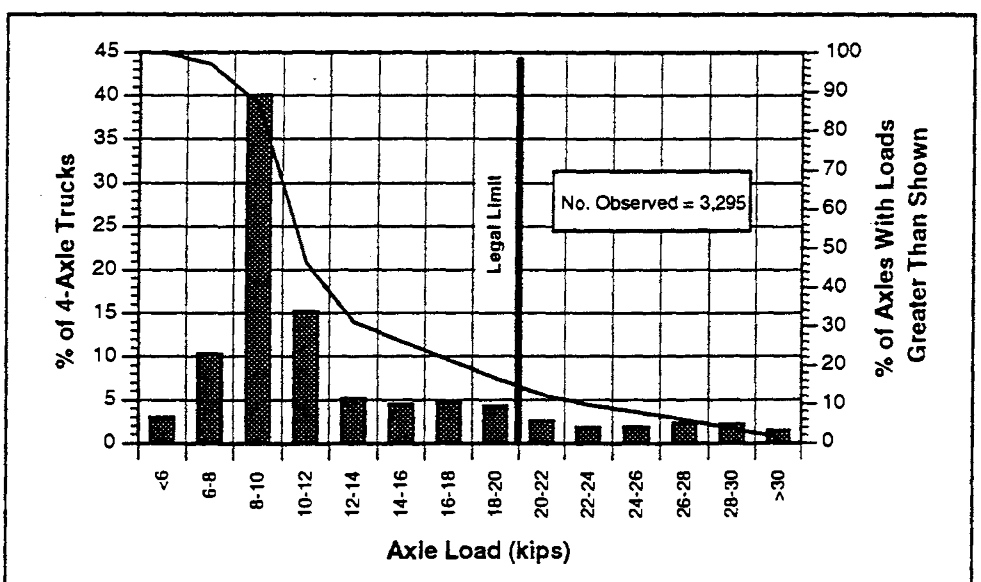

Figure B.18 Axle Loads (Drive Axle), 4-Axle Trucks: Weekday Profile, 5 - 15 July 1994

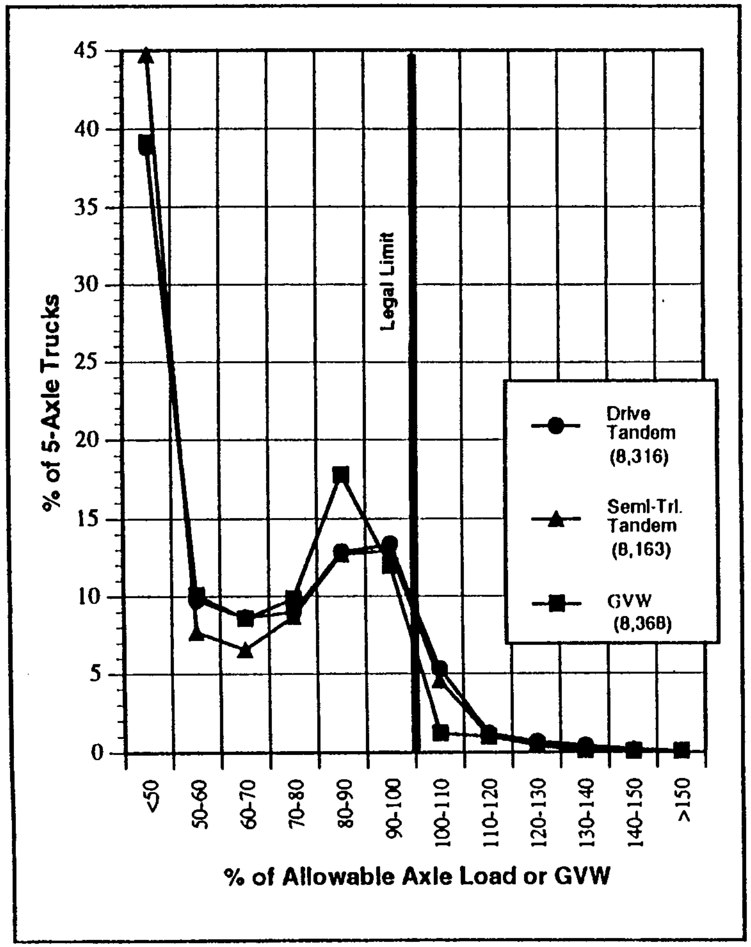

Figure B.19 5-Axle Truck Loads: Weekday Profile, 6 - 17 June 1994

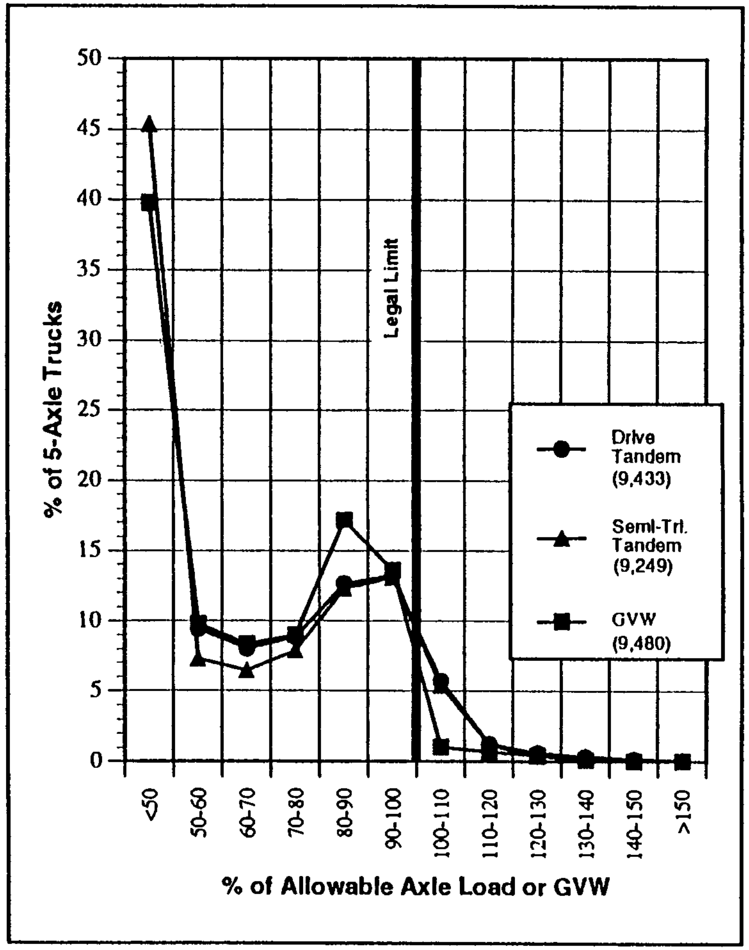

Figure B.20 5-Axle Truck Loads: Weekday Profile, 20 June - 1 July 1994

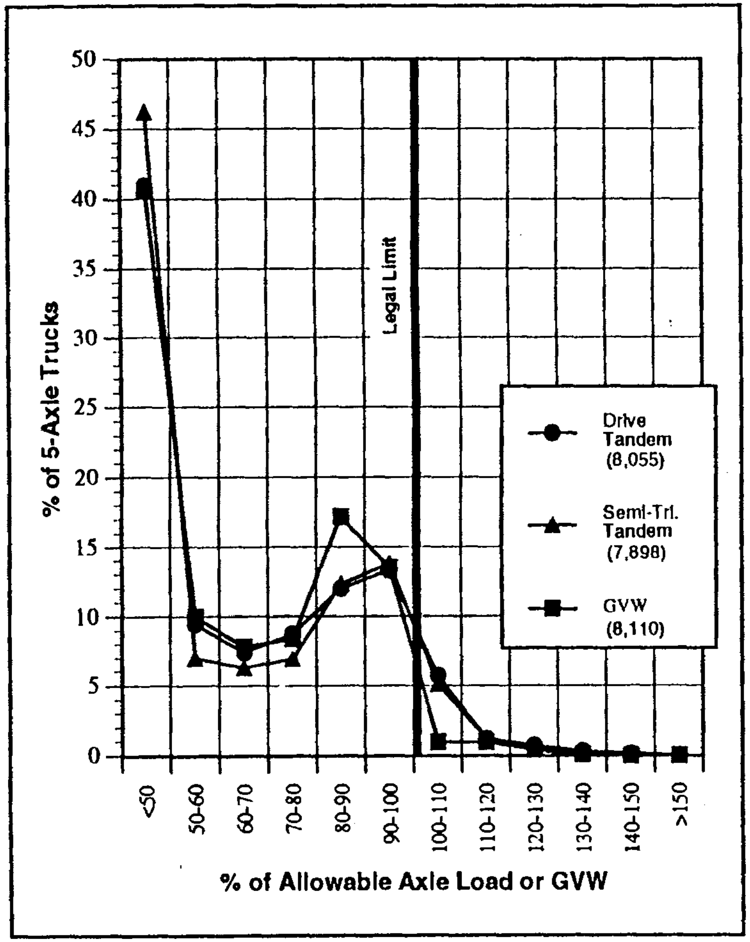

Figure B.21 5-Axle Truck Loads: Weekday Profile, 5 - 15 July 1994

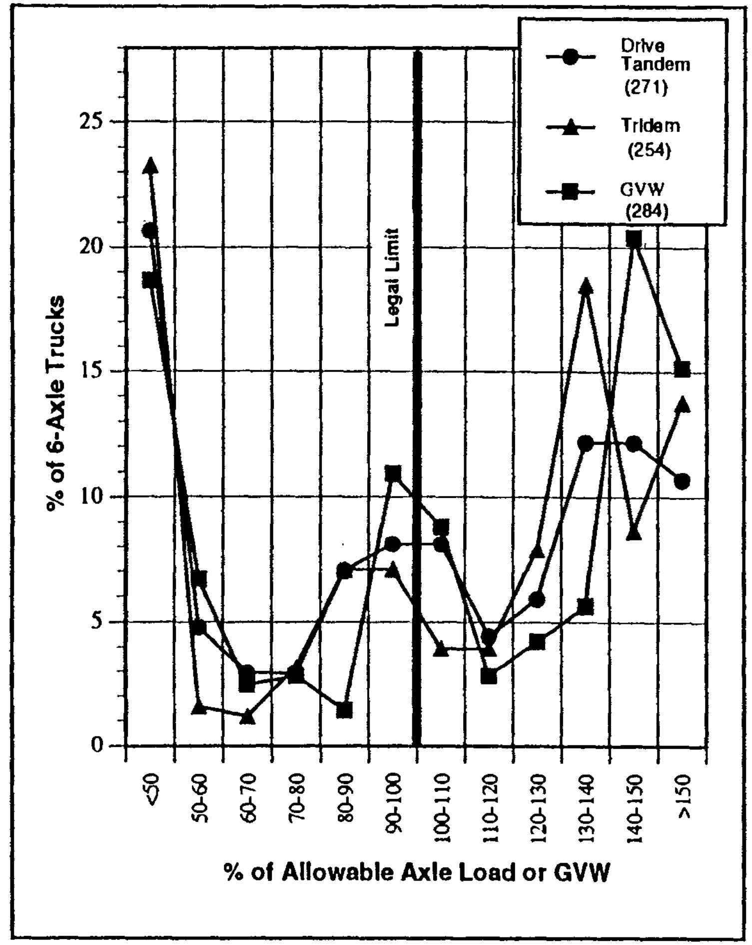

Figure B.22 6-Axle Truck Loads: Weekday Profile, 6 - 17 June 1994

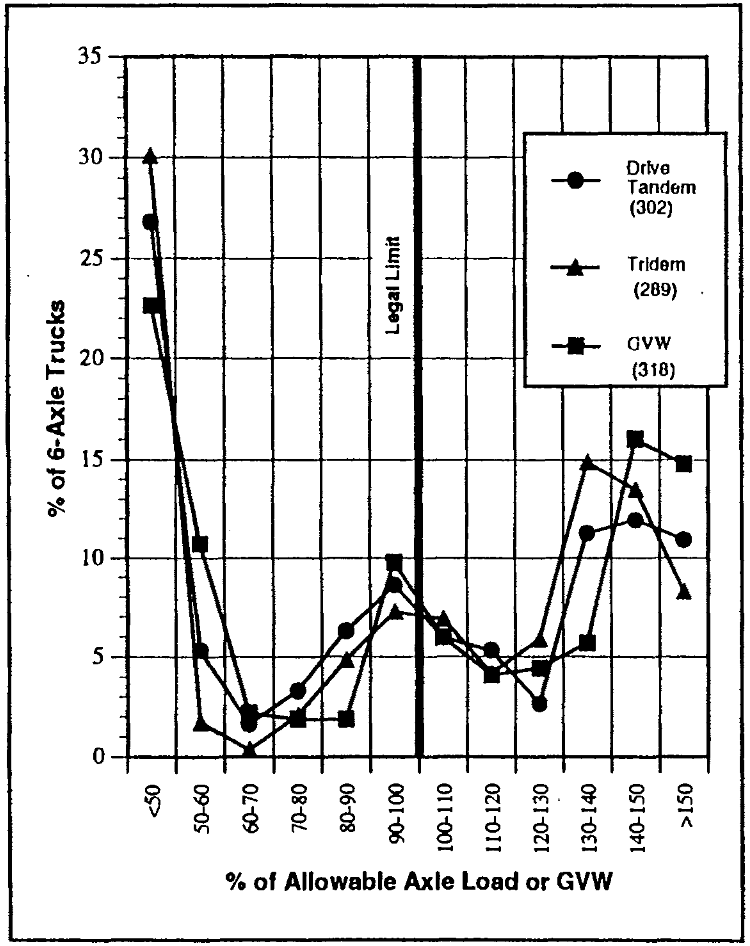

Figure B.23 6-Axle Truck Loads: Weekday Profile, 20 June - 1 July 1994

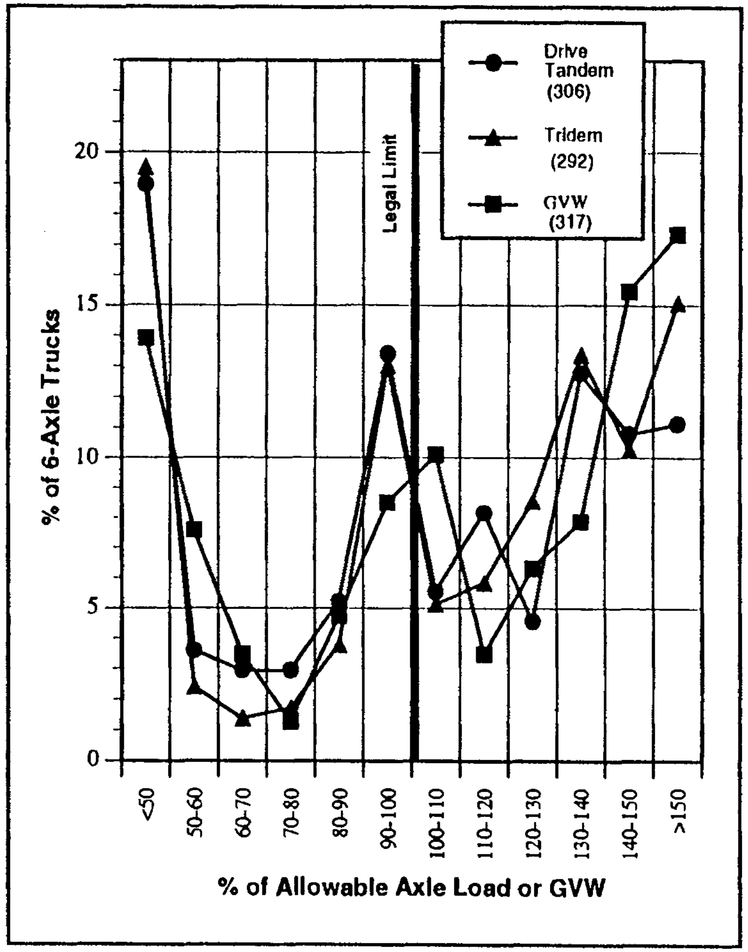

Figure B.24 6-Axle Truck Loads: Weekday Profile, 5 -15 July 1994

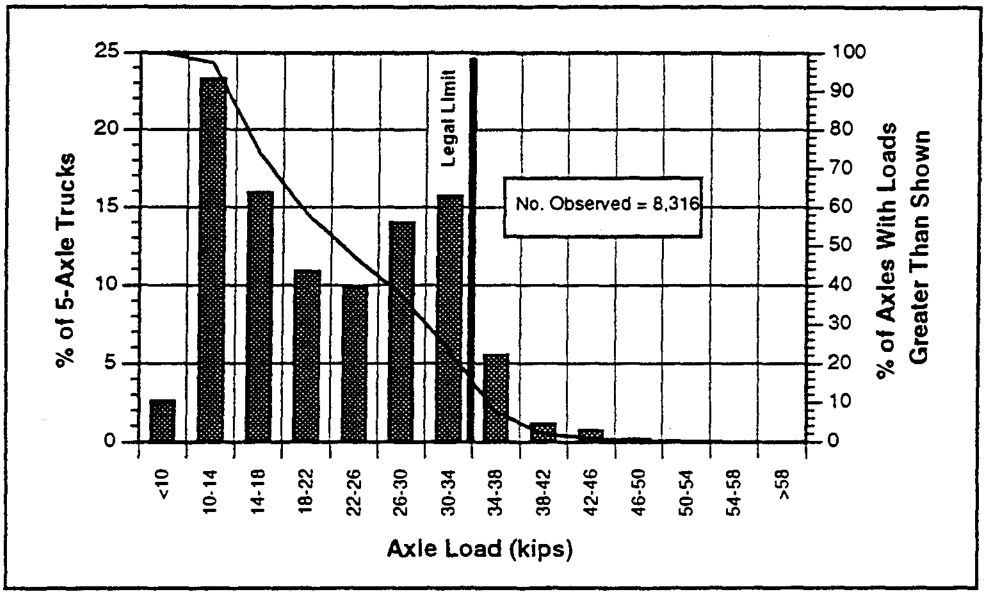

Figure B.25 Axle Loads (Drive Tandem), 5-Axle Trucks: Weekday Profile, 6 - 17 June 1994

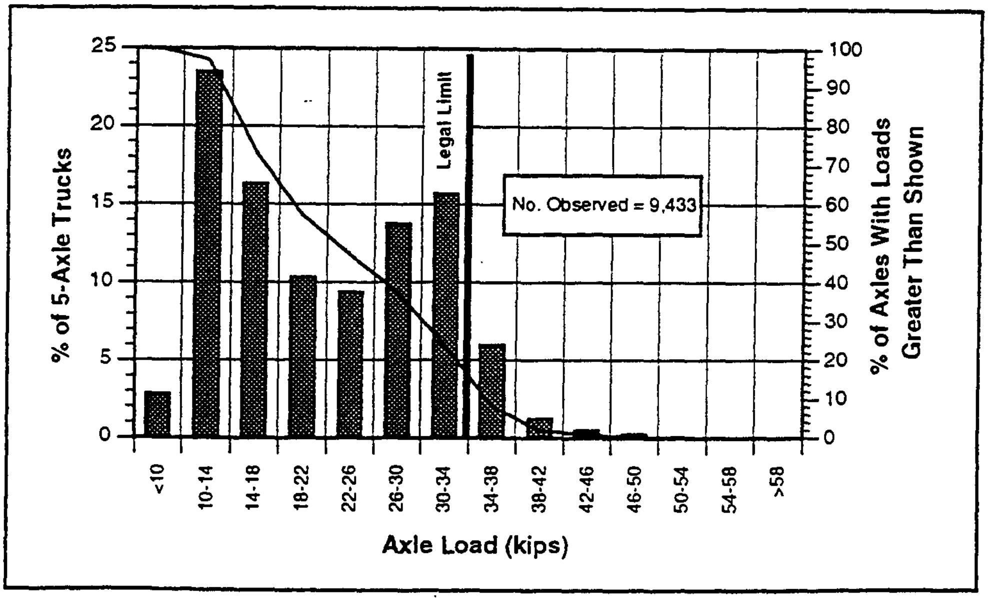

Figure B.26 Axle Loads (Drive Tandem), 5-Axle Trucks: Weekday Profile, 20 June - 1 July 1994

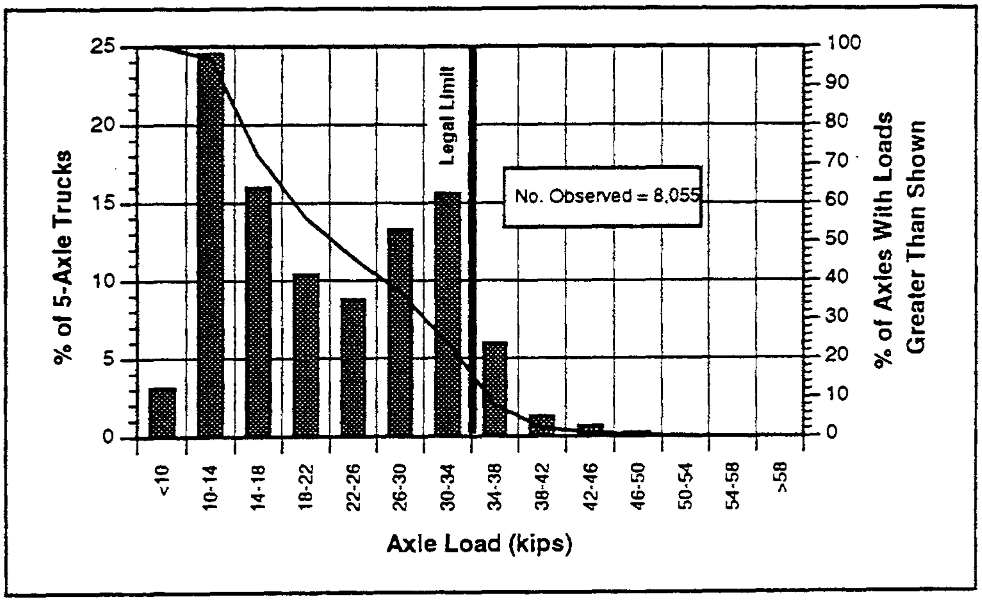

Figure B.27 Axle Loads (Drive Tandem), 5-Axle Trucks: Weekday Profile, 5 - 15 July 1994

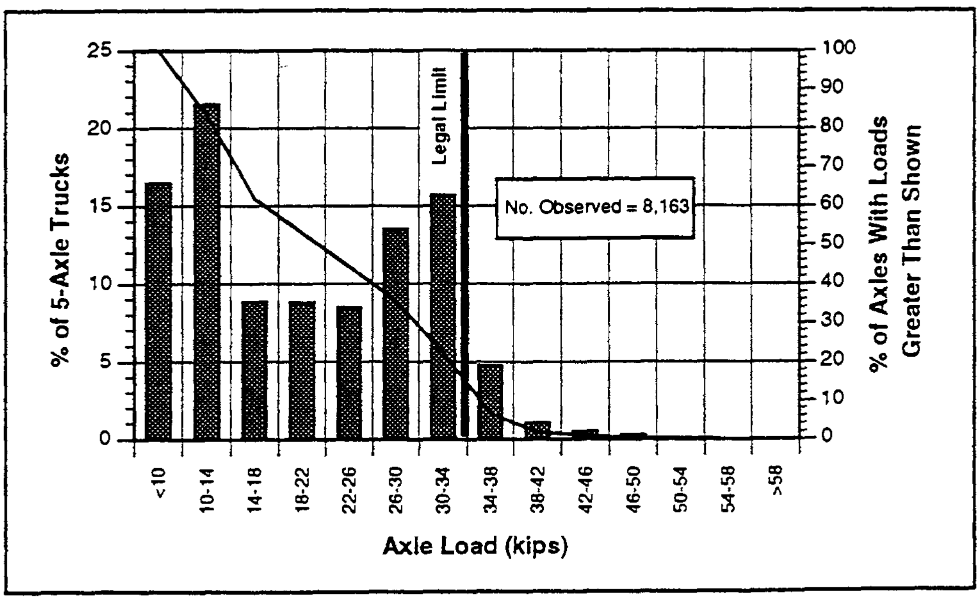

Figure B.28 Axle Loads (Semi-Trl. Tandem), 5-Axle Trucks: Weekday Profile, 6 - 17 June 1994

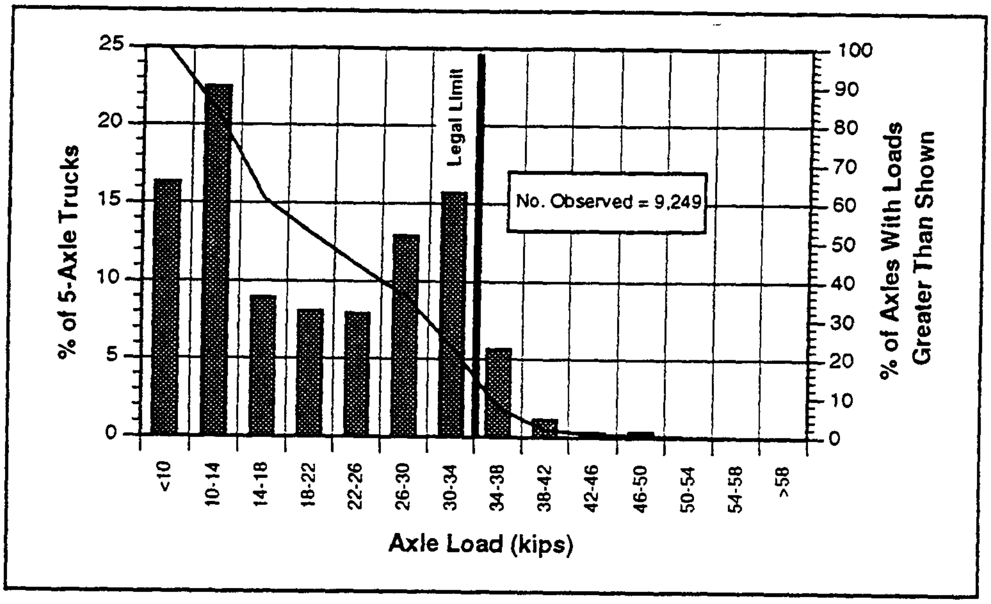

Figure B.29 Axle Loads (Semi-Trl. Tandem), 5-Axle Trucks: Weekday Profile, 20 June - 1 July 1994

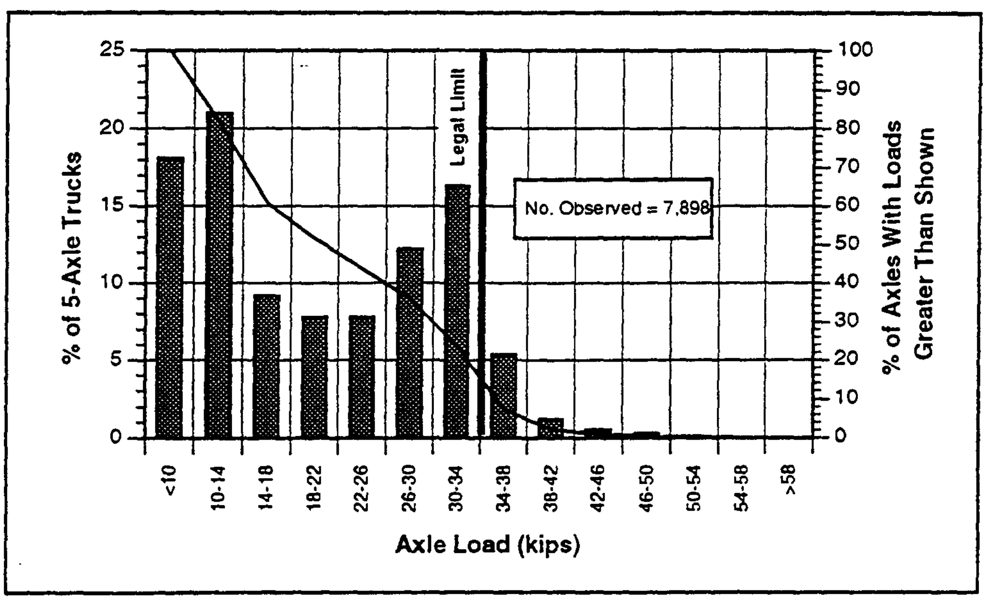

Figure B.30 Axle Loads (Semi-Trl. Tandem), 5-Axle Trucks: Weekday Profile, 5 - 15 July 1994

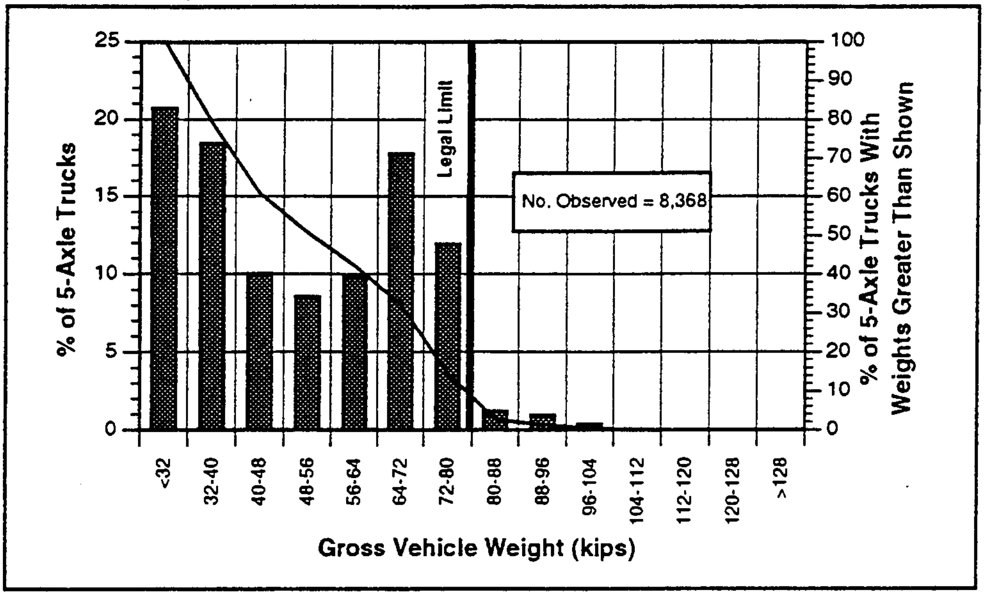

Figure B.31 Gross Vehicle Weights, 5-Axle Trucks: Weekday Profile, 6 - 17 June 1994

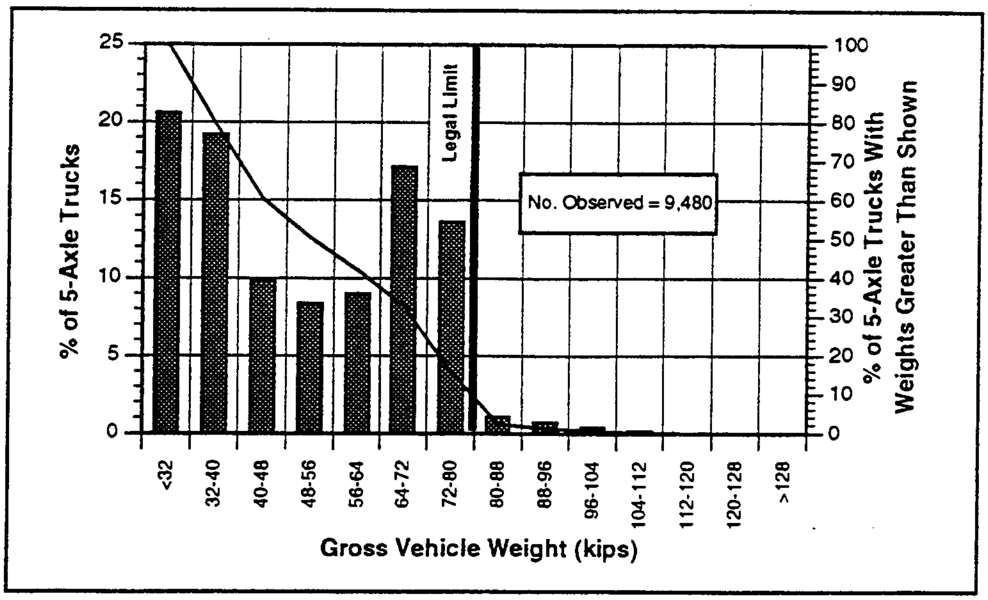

Figure B.32 Gross Vehicle Weights, 5-Axle Trucks: Weekday Profile, 20 June - 1 July 1994

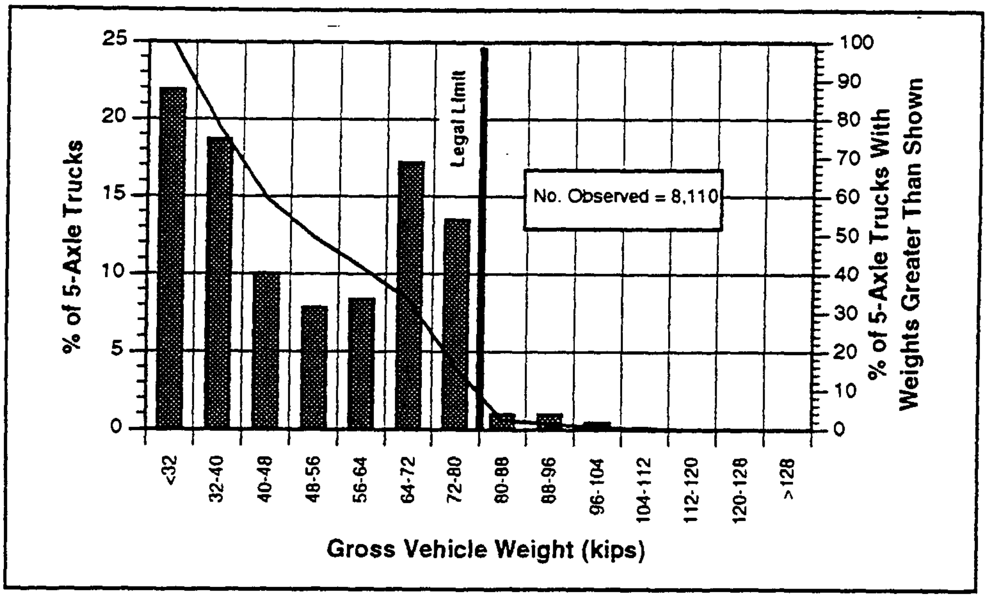

Figure B.33 Gross Vehicle Weights, 5-Axle Trucks: Weekday Profile, 5 - 15 July 1994

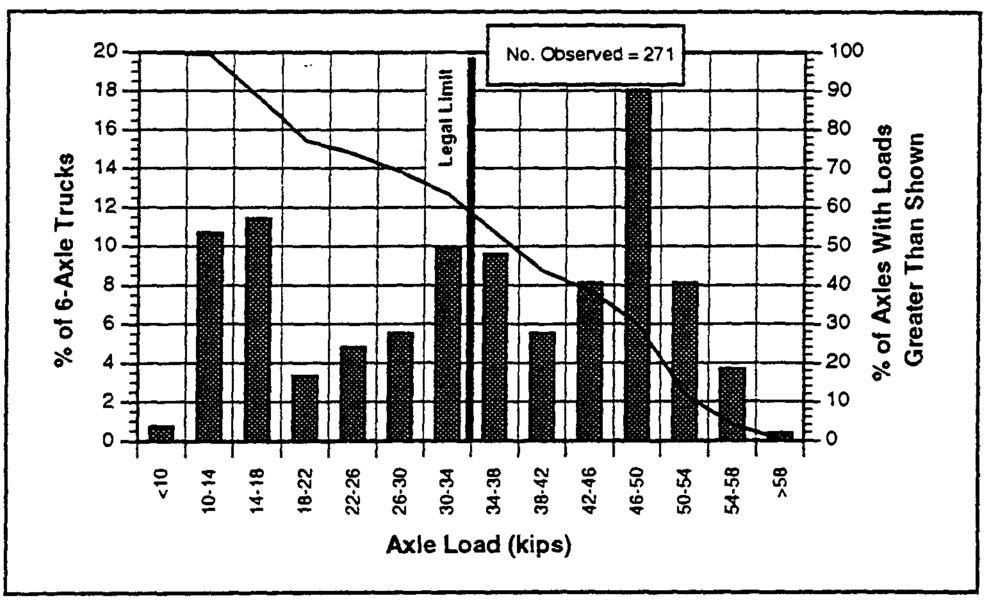

Figure B.34 Axle Loads (Drive Tandem), 6-Axle Trucks: Weekday Profile, 6 - 17 June 1994

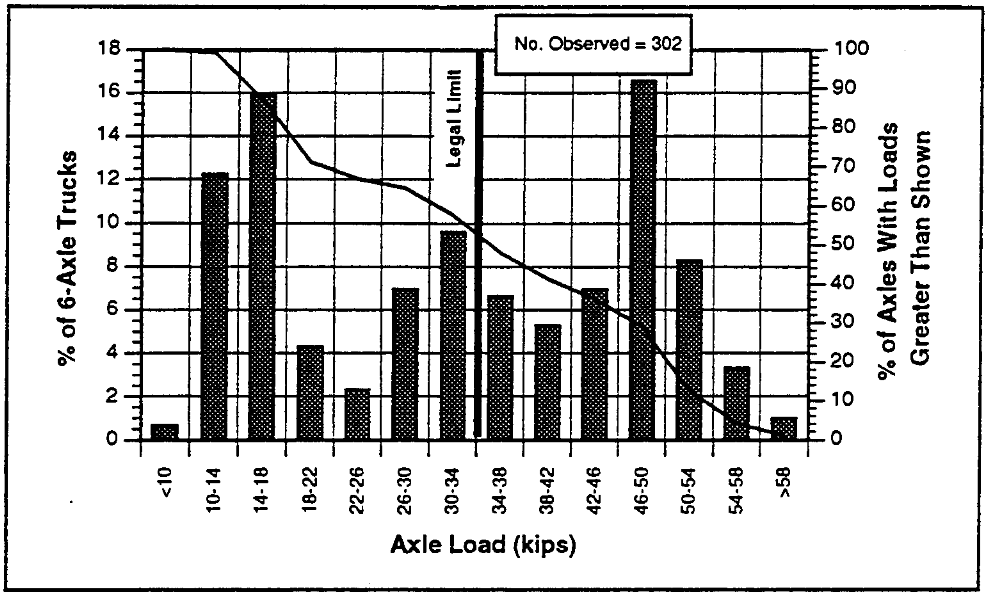

Figure B.35 Axle Loads (Drive Tandem), 6-Axle Trucks: Weekday Profile, 20 June - 1 July 1994

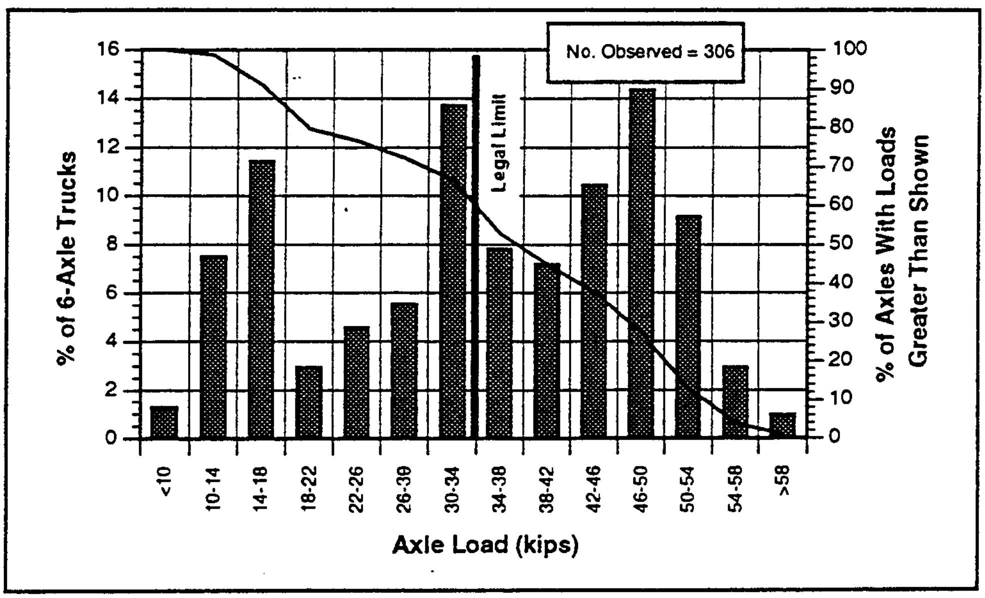

Figure B.36 Axle Loads (Drive Tandem), 6-Axle Trucks: Weekday Profile, 5 - 15 July 1994

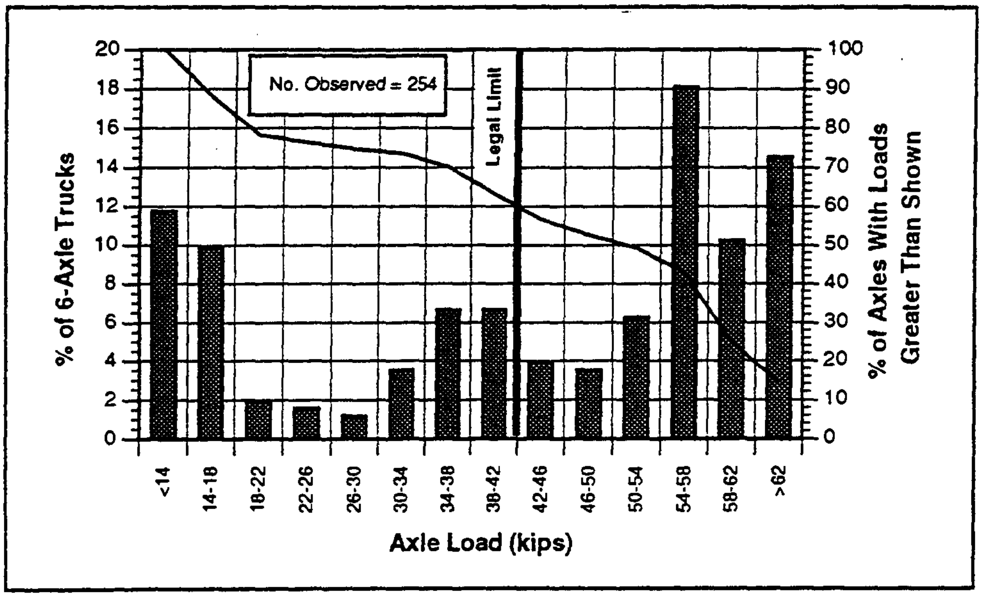

Figure B.37 Axle Loads (Semi-Trl. Tridem), 6-Axle Trucks: Weekday Profile, 6 - 17 June 1994

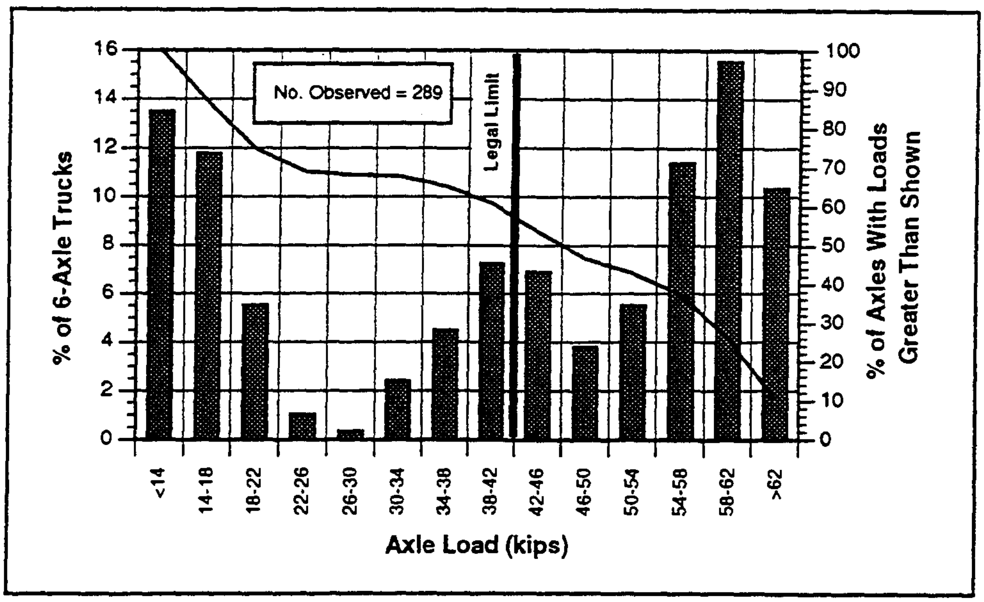

Figure B.38 Axle Loads (Semi-Trl. Tridem), 6-Axle Trucks: Weekday Profile, 20 June - 1 July 1994

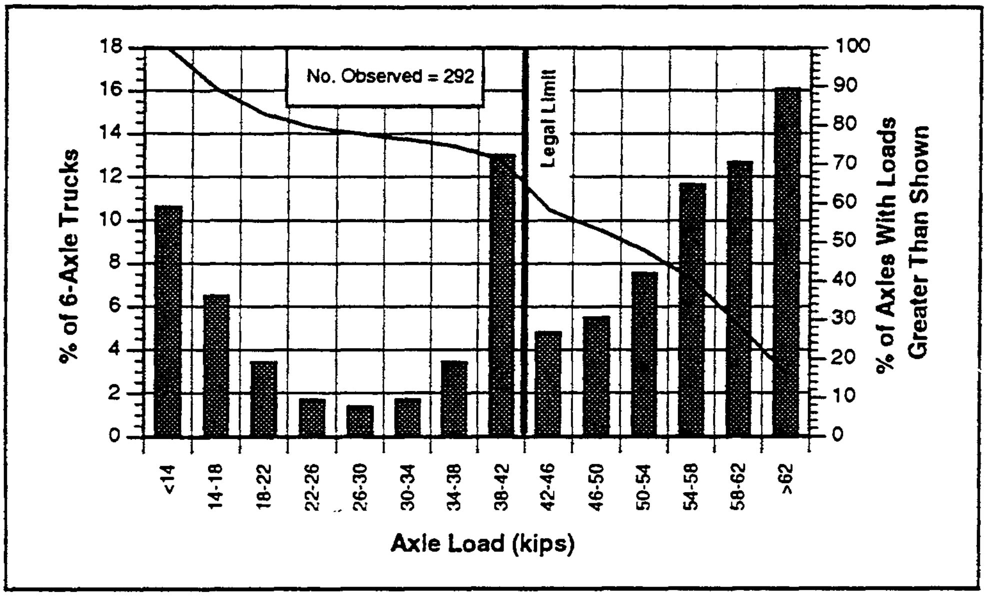

Figure B.39 Axle Loads (Semi-Trl. Tridem), 6-Axle Trucks: Weekday Profile, 5 - 15 July 1994

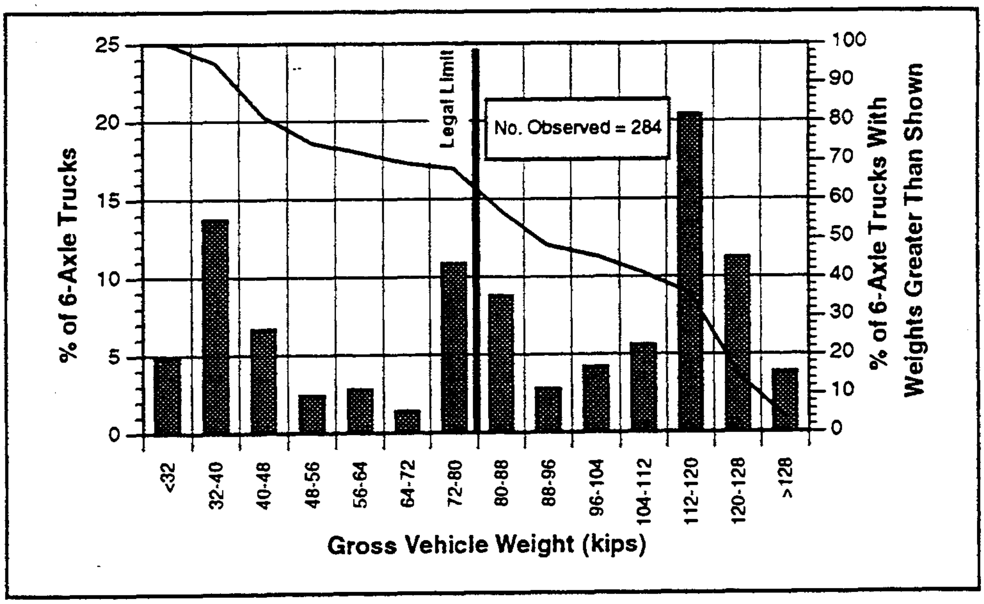

Figure B.40 Gross Vehicle Weights, 6-Axle Trucks: Weekday Profile, 6 - 17 June 1994

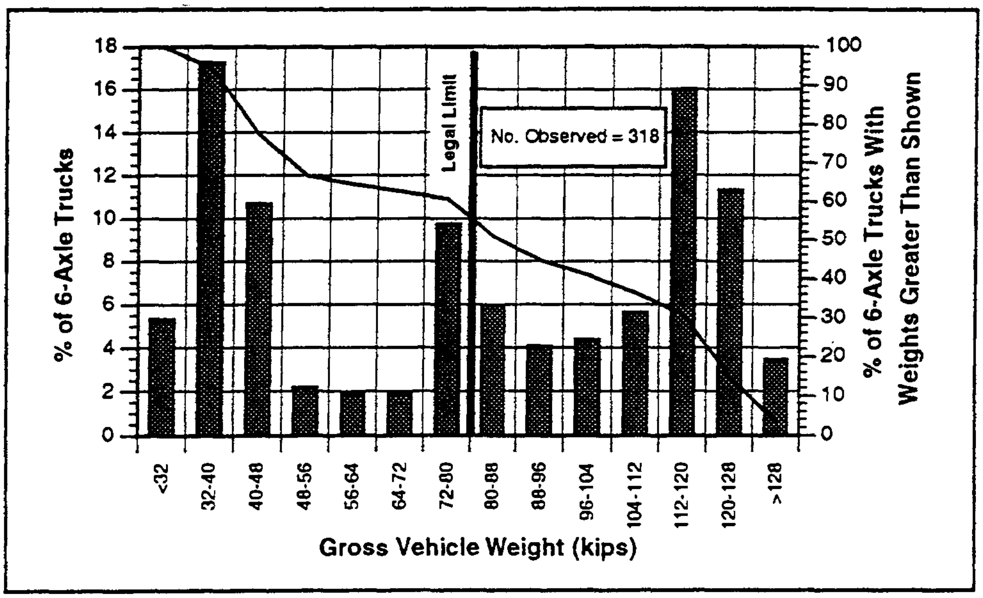

Figure B.41 Gross Vehicle Weights, 6-Axle Trucks: Weekday Profile, 20 June - 1 July 1994

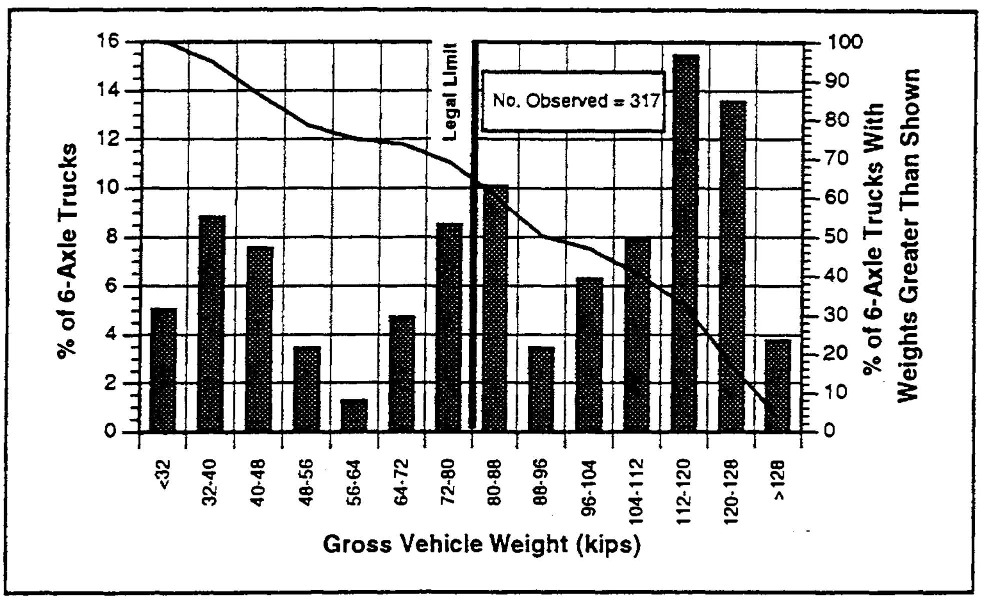

Figure B.42 Gross Vehicle Weights, 6-Axle Trucks: Weekday Profile, 5 - 15 July 1994