MECHANISTIC-BASED ESALS FOR URBAN PAVEMENTS

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ABSTRACT

Equivalent Single Axle Loads (ESALs) have been the standard traffic loading measure used in highway engineering and pavement management practices for decades. However, there are several significant limitations to the application of conventional ESALs for engineering and managing urban pavements systems under modern field state conditions.

The objective of this research was to investigate the use of a typical urban load spectra analysis with weigh-in-motion, as well as falling weight deflection pavement structural response assessment methods, for developing mechanistic-based structural impact load equivalencies that specifically address traffic loading urban field state conditions. This research employed a four-lane weigh-in-motion system installed on Circle Drive within the City of Saskatoon, Saskatchewan, to measure commercial truck load spectra operating across a primary arterial within the City. This research also employed dynamic falling weight deflection measurements taken across standard roadway classes within Saskatoon's road network within the typical range of commercial vehicle load spectra experienced in Saskatoon. The deflection data was integrated with the results of mechanistic frequency sweep characterization of conventional City of Saskatoon road materials in order to differentiate the effect of traffic speed. The commercial load spectra data, primary falling weight deflection measurements and frequency sweep characterization of Saskatoon hot mix asphaltic concrete (HMAC) were integrated to develop mechanistic primary response-based commercial vehicle load equivalency ESAL factors for different classes of roadways and commercial vehicles within the City of Saskatoon.

This research found that the historic method of estimating pavement design life ESAL's may be highly inaccurate for urban field state conditions. This research found that conventional load equivalencies may be up to 700% low when compared to actual pavement primary responses under modern day urban field state conditions. Given the increasing truck traffic as observed in urban centres across Canada, it is recommended that urban road managers adopt mechanistic-based ESALs to more accurately assess the actual field state loading impacts that may be occurring in the field.

Key Words: Equivalent Single Axle Load, weigh-in-motion, pavement, mechanistic analysis

INTRODUCTION

The number of commercial vehicles operating in Saskatchewan, as well as throughout North America, has increased significantly over the past decade (1, 2). Due primarily to the deregulation of the trucking industry in the mid-80's, commercial vehicles have not only grown in number, but have also increased in weight and size (3, 4). As a result, road agencies are finding that roadways are being subjected to vehicle load spectra that are significantly greater than those initially projected, and roadways are subsequently deteriorating at an accelerated rate (5). This is particularly the case on urban corridors with relatively high urbanization and expansion of heavy industry.

Although much empirical evidence exists regarding the performance and weight enforcement of rural pavement systems, there is a lack of knowledge regarding the impact of commercial vehicles, as well as the enforcement of commercial vehicles, on urban roadways (4). As a result, transport literature contains few quantitative research efforts focusing on the effects of commercial loadings on urban roads with little to no information regarding weight enforcement within urban jurisdictions. However, municipalities are beginning to realize the importance of identifying and quantifying the effects of commercial vehicles on the roadway asset life, traffic congestion, and safety, in urban settings.

Recent research has been investigating mechanistic behaviour of flexible pavement structures in an effort to quantify and predict more accurately the field performance of typical road materials and structures under diverse field state conditions. To date this research has shown that typical road materials can be highly sensitive to induced shear stress states, as well as to the rate of loading (6). This is critical in terms of asphaltic pavement performance in that observed traffic patterns on urban roadways tend to operate under reduced speeds, frequent stop-and-go conditions, as well as channelized haul routes, all of which increase the amount of deviatoric loadings on the road structure. As a result, the damage inflicted by commercial vehicles, both overloaded and of legal weight, can be much more drastic than that experienced in a rural environment (6).

STUDY OBJECTIVE

The objective of this research was to evaluate the use of Weigh-In-Motion (WIM) and primary deflection response profiles across various urban road structures to establish the framework for generating mechanistic-based Equivalent Single Axle Load (ESAL) factors representative of typical urban roadway cross-sections.

STUDY SCOPE

This research investigated the use of WIM for collecting traffic load spectra data on an urban freeway in Saskatoon. A video WIM system with integrated video capture technology, located on Circle Drive in Saskatoon, was utilized to capture all vehicle classification and load data. The video WIM system was calibration and its reliability validated as part of the study.

Falling weight deflectometer primary responses on various road classes throughout Saskatoon were utilized to characterize typical primary responses across primary +50% vehicle loads. The primary response results per road class were incorporated with the traffic load spectra obtained from the video WIM site to generate mechanistic-based ESALs representative of urban roadway cross-sections.

METHODOLOGY

The video WIM system was calibrated according to ASTM 1318-02 Type I Bending Plate WIM specifications (7). After eleven days of continuous traffic classification and load data was collected, the reliability of the video WIM system was validated using repeated trial of five different truck types with known weight and configuration. The five trucks, as identified in a previous study of truck traffic trends for the City of Saskatoon, consisted of:

- Two and three axle straight trucks;
- Five and six axle semi-trailers, and;
- Eight axle combination unit.

Heavy Weight Falling Deflectometer data was obtained for various roadway classes throughout the City, including locals, collectors, arterials and freeways/expressways. The range of primary responses of each pavement type to load was applied to each road class in the form of an index representative of:

- Pavement primary deflection response, and;
- PSIPave non-linearity structural index.

Using the commercial vehicle load spectra generated from the freeway location as a base line for comparison, the primary response indices were applied to individual vehicle loads to generate ESALs representative of the actual damage various urban roadway cross-sections.

WIM SYSTEM CALIBRATION

The video WIM system was installed in 2005 on Circle Drive, as illustrated in Figure 1. Circle Drive is a major arterial roadway in Saskatoon and acts as a main truck route and expressway for inter and intra-city traffic, as well as inter-provincial and international traffic. As seen in Figure 2, the WIM system installed on Circle Drive consists of:

- ASTM Type I bending plate WIM systems installed across all four lanes, two northbound and two southbound, for a total of eight bending plates, and loop arrays prior to and after the bending plates in each lane (for a total of eight).
- A video capture system that includes two side imaging cameras (side-fire cameras) and two license plate cameras.

The side-fire cameras are installed on either side of the roadway and are triggered by vehicles in both the driving and passing lanes for the specific direction of travel. The license plate cameras are installed only over the driving lanes of each direction of travel and are triggered by vehicles traveling in those lanes. Images are recorded by the side-fire and license plate cameras and are linked with their corresponding WIM vehicle record through the system electronics. The WIM bending plate system records the gross vehicle weight, as well as individual axle weights, vehicle length, speed and classification for all vehicles in all lanes.

All four lanes of the video WIM system were calibrated by International Road Dynamics (IRD) Inc. on May 15, 2006, using a six-axle semi-trailer of known dimension and weight, following the ASTM 1318-02 guidelines (7), with a 95% tolerance of:

- ±20% for axle load;
- ±15% for axle group load, and;
- ±10% for gross vehicle weight (GVW).

After the initial calibration results, the eastbound and westbound driving lanes had the highest average percent difference between the WIM-measured steering axle weights and the actual steering axle weight, at 7.87% and 3.15%, respectively. The eastbound and westbound driving lanes also displayed the highest average percent difference in measured versus actual weights for the trailer axle groups, at -3.80% and -4.88%, respectively, as well as the highest average standard deviations, at 6.11 and 6.05, respectively. The percent difference between the measured GVW and actual GVW ranged from -1.93% in the westbound driving lane to 0.94% in the eastbound passing lane. The largest differences were apparent in the driving lanes, at -1.93% for the WB and -1.38% for the EB. The results of the initial calibration results show that the WIM scales were all producing errors within the standards prescribed in ASTM 1318-02 Type I WIM specifications (7).

WIM SYSTEM VALIDATION

Once the calibration of the Video WIM system was complete, validation of the WIM system was evaluated using five test vehicle configurations representative of the vehicle types typically operating on Circle Drive in Saskatoon. The five commercial vehicle configurations used in the system validation testing included:

- Two axle straight truck (Class 4);

- Three axle straight truck (Class 5);
- Five axle semi-trailer unit (Class 12);
- Six axle semi-trailer unit (Class 13), and;
- Eight axle B-train unit (Class 19).

The reliability analysis was completed with 15 repeat trials of each truck configuration at a known static weight across the WIM scales within a speed range of 60 to 80 km/h, which is representative of the lowest speed bin in the WIM system classification algorithm and typical operating speeds of commercial vehicles on this section of Circle Drive. The identity of the test truck within the traffic stream was confirmed using the video capture technology accompanying the WIM system on Circle Drive, as illustrated in Figure 3.

The video capture capabilities of the system included images of the license plate and the side of the test truck. However, license plate capture cameras were only configured for the curb lanes in both directions. Also, the side imaging cameras, though capable of capturing vehicle images in both the median and curb lanes, were configured primarily for the curb lanes, leading to the possible situation where an adequate image of the truck in the median lane could not be captured if a vehicle were present in the curb lane at the same time. Based on the calibration results, the reliability of the WIM scales was only validated for the curb lanes and the assumption was made that the median lanes would exhibit similar trends as those observed in the corresponding curb lane because the lanes were calibrated together.

For the purpose of the validation of the reliability of the WIM system, weight measurements from each trial for the steering axle group, drive axle group, trailer axle groups, and GVW were recorded and adjusted in order to compensate for the remaining error in the system post-calibration. The sample mean, range, standard deviation and coefficient of variance were assessed for all groups of measurement (steering, drive and trailer axles and GVW) in order to assess the uniformity within the weight measurements.

The same truck type and vehicle components, as well as driver and weighting material (non-liquid), were used for the five, six and eight axle semi-trailer combination unit measurements. For the purpose of the five, six and eight axle truck testing, the driver and all units were donated in kind from Pavement Scientific International Inc. For the purpose of the two and three axle straight truck measurements, the same driver and weighting (soil and gravel) was used for both, but two different trucks were used, all of which were borrowed from the City of Saskatoon.

The reliability assessment of the westbound curb lane WIM system, summarized in Figure 4, indicated that the largest mean percent difference between the WIM weight measurements and static weight measurements may be expected within the steering axle group weight records for the two and three axle straight truck configurations, as well as the eight axle semi-trailer combination unit configuration. In contrast, the drive axle group WIM weights are expected to have the largest mean difference for the five axle semi-trailer combination unit configuration and the trailer tridem axle group for the six axle semi-trailer combination unit configuration. Regardless, all of the axle group mean percent differences were within the ASTM (7) specified 15% range of the static weight and the GVW mean percent difference for all vehicle configurations was within the ASTM (7) specified 10% range of the static GVW.

The reliability assessment of the eastbound driving lane WIM system, illustrated in Figure 5, displayed somewhat similar trends regarding the largest mean percent difference between the WIM weight and the static weight measurements, where the three, five and eight axle configurations exhibited the largest variances within the steer axle group. However, in contrast to the westbound system, the two axle straight truck displayed significant mean differences within the drive axle group weights and the six axle semi-trailer combination unit showed greatest mean difference within the trailer tridem axle group weights. Also, the reliability assessment results for all five truck configurations confirm that the WIM measurements taken in the eastbound curb lane are exhibiting higher variability as compared to the WIM measurements collected from the westbound lane, as was initially postulated from the results of the initial system calibration. Regardless, all of the axle group mean percent differences were within the ASTM (7) specified 15% range of the static weight and the GVW mean percent difference for all vehicle configurations was within the ASTM (7) specified 10% range of the static GVW.

COMMERCIAL VEHICLE TRAFFIC CLASSIFICATION DISTRIBUTION

WIM vehicle data was collected on a 24-hour basis from May 12, 2006, to May 22, 2006, for a total of 264 consecutive hours of data collection. For the purpose of this analysis, truck configurations were assessed according to the classification system summarized in Table 1, based on the Saskatchewan Department of Highways and Transportation classification system. All Class 4 vehicles (two axle straight trucks) weighing less than 6,000 kg were removed from the analysis in order to exclude the effects of private, non-commercial use vehicles on the truck traffic spectra analysis.

An average daily truck volume of 2,144 trucks per day (tpd) was observed across the four lanes of the Circle Drive site, generating a total of 23,584 truck WIM records during the study. As summarized in Figure 6, the majority of the truck population consisted of class 4, 5, 6, 11, 12, 13 and 19 vehicles, contributing to 96% of the total observed truck population.

Due to the significant presence of the Class 4, 5, 6, 11, 12, 13 and 19 truck configurations in the recorded truck traffic stream, the commercial vehicle spectra analysis was completed only for the seven truck configurations under the assumption that they would represent the majority of the population and exhibit the major weighting trends present at the study site.

Individual truck data records were analyzed for a consecutive seven day period, from Friday, May 12th until Thursday, May 18th, 2006. The seven day analysis of the seven major truck configurations was found to be representative of 70% of the actual captured truck traffic stream, contributing 16,525 truck records, as illustrated in Figure 7.

Based on the commercial truck trends observed over the seven day period of analysis, 49% of the study vehicles were found to travel in the eastbound direction, with 68% traveling in the eastbound curb lane (Lane 1). The remaining 51% of the vehicles were observed traveling in the westbound direction, with 85% in the westbound curb lane (Lane 4). The resulting total vehicle distribution from the seven day analysis period is illustrated in Table 2 and closely resembled the distribution trends observed across the entire data-capture period, thereby confirming that this sample adequately represented the entirety of the collected data.

COMMERCIAL VEHICLE LOAD SPECTRA DISTRIBUTION BY VEHICLE CLASS

Analysis of the average and maximum axle group loads by vehicle configuration is summarized in Figure 8. The average weights of the steering axle groups for each vehicle configuration was relatively consistent throughout the data set, ranging from 2,538 kg for the four axle tractor and semi-trailer (Class 11) to 5,809 kg for the three axle straight truck (Class 5). However, analysis of the maximum recorded steering axle group weights showed that the straight truck configurations (Classes 4, 5 and 6) tended to vary more significantly and have higher maximum weights for than the other vehicle configurations. This phenomenon was observed once more for the drive axle groups, where the three and four axle straight trucks (Class 5 and 6), despite their lower average weight, exhibited larger maximum drive axle group weights than the larger classes. With respect to the trailer tridem and tandem axle group weights, both axle groups showed similarities between the six and eight axle trucks (Class 13 and 19), as well as the five and eight axle trucks (Class 12 and 19), with the respective Class 19 axle groups weighing slightly more than its Class 12 and 13 counterparts. This was expected because the axle configurations and trailer units are similar between the vehicle types. The Class 11 vehicles, though similar in trailer tandem maximum weight range to the Class 12 and 19 configurations, had a much lower average weight, possibly indicative of a specialized commodity range as compared to the other two configurations.

Since the results of the vehicle distribution by lane indicated that the majority of the vehicles traveled in the curb lanes, only the curb lanes of either direction were assessed further. A one-tailed analysis was also completed in order to determine the scope of predictability of the ESALs within the captured truck population, as represented by 68th and 95th percentile probability bands.

Table 3 summarizes the GVW ESALs (mean, 68th percentile and 95th percentile) for each of the major truck classes in the westbound and eastbound curb lanes. Figure 9 summarizes the mean and 95th percentile GVW ESAL loads for both eastbound and westbound curb lanes. The trends observed within both illustrate an expected increase in both the mean and probability bands as truck size increases from Class 4 (two axle straight truck) to Class 19 (eight axle combination unit), with the exception of Class 6 and 11 configurations. The Class 11 configurations in both directions exhibit the lowest GVW ESAL trends as compared to the other tractor and semi-trailer combination units. In contrast, the westbound Class 6 configurations show similar GVW ESAL trends to those observed for two and three axle straight trucks, whereas the eastbound Class 6 vehicles show significant increased in GVW ESAL trends, with mean load and probability bands mirroring those obtained for the Class 19 vehicles. This indicates that the majority of the eastbound four axle straight trucks are loaded in comparison to those traveling in the westbound direction.

Class 4 Load Distribution

The one-tailed cumulative distribution of Class 4 ESALs per vehicle is illustrated for the westbound and eastbound curb lanes in Figure 10. As seen in Figure 10, the 68th percentile, represented by the first coloured segment (grey segment) was 2.02 ESALs in the westbound direction and contained approximately 90% of the observed westbound Class 4 vehicles. The 95th percentile, represented as the sum of the first and second coloured segments, occurred at 3.2 ESALs and contained approximately 95% of the westbound Class 4 vehicle population. As seen in Figure 10, the 68th percentile, represented by the first coloured segment (grey segment), was slightly higher than the westbound direction, at 2.24 ESALs in the eastbound direction, and contained approximately 88% of the observed eastbound Class 4 vehicles. The eastbound 95th percentile, or mean plus two standard deviations, occurred at 3.48 ESALs, also larger than the 95th percentile load observed for Class 4 vehicles in the westbound lane, and contained approximately 95% of the eastbound Class 4 vehicle population. Consequently, one-tailed analysis of the cumulative Class 4 ESAL distribution within both the westbound and eastbound curb lanes indicated that the Class 4 vehicles in the eastbound curb lane were marginally heavier than those captured traveling in the westbound curb lane.

Class 5 Load Distribution

The one-tailed cumulative distribution of Class 5 ESALs per vehicle is illustrated for the westbound and eastbound curb lanes in Figure 11. As seen in Figure 11, the 68th percentile, represented by the first coloured segment (grey segment) was 2.68 ESALs in the westbound direction and contained approximately 88% of the observed westbound Class 5 vehicles. The 95th percentile, represented as the sum of the first and second coloured segments, occurred at 4.19 ESALs and contained approximately 96% of the westbound Class 5 vehicle population. As seen in Figure 11, the 68th percentile, represented by the first coloured segment (grey segment), was slightly lower than the westbound direction, at 2.37 ESALs in the eastbound direction, and contained approximately 86% of the observed eastbound Class 5 vehicles. The eastbound 95th percentile, or mean plus two standard deviations, occurred at 3.53 ESALs, also lower than the 95th percentile load observed for Class 5 vehicles in the westbound lane, and contained approximately 96% of the eastbound Class 5 vehicle population. In contrast to the trends observed for Class 4 vehicles, one-tailed analysis of the cumulative Class 5 ESAL distribution within both the westbound and eastbound curb lanes indicated that the Class 5 vehicles in the eastbound curb lane were lighter than those captured traveling in the westbound curb lane.

Class 6 Load Distribution

The one-tailed cumulative distribution of Class 6 ESALs per vehicle is illustrated for the westbound and eastbound curb lanes in Figure 12. As seen in Figure 12, the 68th percentile, represented by the first coloured segment (grey segment) was 1.97 ESALs in the westbound direction and contained approximately 94% of the observed westbound Class 6 vehicles. The 95th percentile, represented as the sum of the first and second coloured segments, occurred at 3.56 ESALs and contained approximately 97% of the westbound Class 6 vehicle population. As seen in Figure 12, the 68th percentile, represented by the first coloured segment (grey segment), was significantly higher than the westbound direction, at 5.02 ESALs in the eastbound direction, and contained approximately 90% of the observed eastbound Class 6 vehicles. The eastbound 95th percentile, or mean plus two standard deviations, occurred at 7.58 ESALs, also significantly higher than the 95th percentile load observed for Class 6 vehicles in the westbound lane, and contained approximately 97% of the eastbound Class 6 vehicle population. In contrast to the trends observed for the westbound Class 6 vehicles, one-tailed analysis of the cumulative Class 6 eastbound ESAL distribution indicated significant directional difference in loading magnitude. These differences may have been caused by commodity type and loaded vs. empty haul routes. For example, cement plants located on the west side of the City utilizing Circle

Drive to gain access to projects on the east side of the City. Consequently, said trucks would be travel eastbound loaded, drop their load, and return to the plant (westbound) empty for another load.

Class 11 Load Distribution

The one-tailed cumulative distribution of Class 11 ESALs per vehicle is illustrated for the westbound and eastbound curb lanes in Figure 13. As seen in Figure 13, the 68th percentile, represented by the first coloured segment (grey segment) was 1.27 ESALs in the westbound direction and contained approximately 92% of the observed westbound Class 11 vehicles. The 95th percentile, represented as the sum of the first and second coloured segments, occurred at 2.17 ESALs and contained approximately 94% of the westbound Class 11 vehicle population. As seen in Figure 13, the 68th percentile, represented by the first coloured segment (grey segment), was similar to westbound direction, at 1.39 ESALs in the eastbound direction, and contained approximately 91% of the observed eastbound Class 11 vehicles. The eastbound 95th percentile occurred at 2.34 ESALs, also similar to the westbound lane, and contained approximately 97% of the eastbound Class 11 vehicle population. Based on a comparison of the cumulative ESAL distributions within both curb lanes, no major directional trends were interpolated.

Class 12 Load Distribution

The one-tailed cumulative distribution of Class 12 ESALs per vehicle is illustrated for the westbound and eastbound curb lanes in Figure 14. As seen in Figure 14, the 68th percentile, represented by the first coloured segment (grey segment) was 3.39 ESALs in the westbound direction and contained approximately 82% of the observed westbound Class 12 vehicles. The 95th percentile, represented as the sum of the first and second coloured segments, occurred at 4.96 ESALs and contained approximately 96% of the westbound Class 12 vehicle population. As seen in Figure 14, the 68th percentile was lower than the westbound direction, at 2.72 ESALs in the eastbound direction, and contained approximately 84% of the observed eastbound Class 12 vehicles. The eastbound 95th percentile occurred at 4.01 ESALs, also lower than the 95th percentile load observed for Class 12 vehicles in the westbound lane, and contained approximately 95% of the eastbound Class 12 vehicle population. Similar to the directional trends observed for Class 5 vehicles, one-tailed analysis of the cumulative ESAL distribution within both the westbound and eastbound curb lanes indicated that the Class 12 vehicles traveling in the eastbound curb lane were lighter than those captured traveling in the westbound curb lane.

Class 13 Load Distribution

The one-tailed cumulative distribution of Class 13 ESALs per vehicle is illustrated for the westbound and eastbound curb lanes in Figure 15. As seen in Figure 15, the 68th percentile, represented by the first coloured segment (grey segment) was 3.15 ESALs in the westbound direction and contained approximately 81% of the observed westbound Class 13 vehicles. The 95th percentile, represented as the sum of the first and second coloured segments, occurred at 4.61 ESALs and contained approximately 97% of the westbound Class 13 vehicle population. As seen in Figure 15, the 68th percentile was slightly higher than the westbound direction, at 3.22 ESALs in the eastbound direction, and contained approximately 82% of the observed eastbound Class 13 vehicles. The eastbound 95th percentile occurred at 4.74 ESALs, also slightly higher than the 95th percentile load observed for westbound Class 13 vehicles, and contained approximately 95% of the eastbound Class 13 vehicle population. Similar to the directional trends observed for Class 4 vehicles, one-tailed analysis of the cumulative ESAL distribution within both the westbound and eastbound curb lanes indicated that the Class 13 vehicles in the eastbound curb lane were slightly heavier than those captured traveling in the westbound curb lane.

Class 19 Load Distribution

A one-tailed cumulative distribution of Class 19 ESALs per vehicle is illustrated for the westbound and eastbound curb lanes in Figure 16. As seen in Figure 16, the 68th percentile, represented by the first coloured segment (grey segment) was 5.93 ESALs in the westbound direction and contained approximately 86% of the observed westbound Class 19 vehicles. The 95th percentile, represented as the sum of the first and second coloured segments, occurred at 8.47 ESALs and contained approximately 98% of the westbound Class 19 vehicle population. As seen in Figure 16, the 68th percentile, represented by the first coloured segment (grey segment), was similar to the westbound direction, at 5.89 ESALs in the eastbound direction, and contained approximately 81% of the observed eastbound Class 19 vehicles. The eastbound 95th percentile occurred at 8.67 ESALs, also similar to the westbound lane, and contained approximately 97% of the eastbound Class 19 vehicle population. The similarity between the westbound curb lane and eastbound curb lane cumulative distributions indicates that there is typically little variance between traffic patterns in the two directions. This may possibly be indicative of the differences in routing and commodity between long-haul and short-haul vehicles.

FREEWAY COMMERCIAL VEHICLE CUMULATIVE ESALs

The cumulative ESALs of each of the representative vehicle classes for the seven day study period are summarized in Table 4 and Figure 17. A total of 11,420 GVW ESALs were captured in the westbound curb lane across the seven vehicle classes during the seven day study period. As seen in Table 4, the majority of the westbound GVW ESALs were contributed by Class 12 and Class 19 vehicles, at approximately 30% of the recorded GVW ESALs each. Figure 17 also indicates that Class 12 and 19 vehicles contributed the majority of the ESALs for the drive axle group, contributing over 50% of the total drive axle group ESALs between the two classes. The cumulative steer axle group ESALs showed that the majority of the ESALs were contributed by Class 5 vehicles, as would be expected due to the larger mean loads and variances within the steer axle group loads by vehicle.

As illustrated in Table 4, a total of 2,561 ESALs were recorded for the westbound curb lane steer axle group, with 33% contributed by Class 5 vehicles and 30% by Class 12 vehicles. The overrepresentation of Class 5 and Class 12 vehicles within the cumulative ESAL distribution was expected since both classes exhibited the greatest presence within the observed population, at 20% and 33% of the population, respectively, followed closely by Class 4 and 19 vehicles, which contributed to 17% 15% of the population, respectively.

As seen in Table 4 and Figure 18, a total of 8,860 GVW ESALs were captured in the eastbound curb lane from the seven vehicle classes during the analysis period. Continuing with the GVW ESAL trends observed in the westbound curb lane, the majority of the eastbound GVW ESALs were contributed by Class 12 and Class 19 vehicles, at 25% and 31% of the total recorded ESALs, respectively. Figure 18 indicates that Class 4 vehicles, in addition to Class 12 and 19 vehicles, contributed the majority of the ESALs for the drive axle group, with each class contributing 21% to 23% of the total drive axle group ESALs.

As illustrated in Table 4 and Figure 18, the cumulative eastbound curb lane ESALs observed for the steer axle groups indicated that the majority of the steer axle group ESALs were contributed by Class 5 and 12 vehicles, as would be expected due to the larger mean steer axle group loads per vehicle observed during the individual mean load assessment and their greater representation in the observed vehicle population. A total of 2,224 ESALs were recorded for the steer axle group, of which Class 5 and 12 vehicles contributed more than half of the recorded loads.

Combining the cumulative ESALs obtained for the westbound and eastbound curb lanes, as illustrated in Figure 18 indicates that the majority of the cumulative ESALs were contributed by Class 12 and Class 19 vehicles, representative of five axle semi-trailers and eight axle combination units.

ESALS BY ROADWAY CLASS

Pavement Scientific International (PSI) Inc. completed a comprehensive asset management pilot project for the City of Saskatoon involving the use of Ground Penetrating Radar (GPR) and Heavy Weight Falling Deflectometer (HWD) non-destructive testing along various roadways and road types throughout Saskatoon in 2006. Utilizing a method of ratio comparison between the primary response data of the expressways versus the other urban road types, in conjunction with the ESAL load spectra obtained from the Circle Drive Video WIM site, the ESAL factor were calculated by vehicle class and road class. Resulting from the project, several measures of roadway deflection and non-linear elasticity were obtained under primary weights (44.7 kN) for various urban roadway types (8), including:

- Expressway and freeway;
- Arterial;
- Collector and local, and;
- Local-Industrial road types.

The HWD and GPR response measurements of the pavements were taken in the same locations where the deflection response measurements were obtained. The deflection and non-linear elastic responses were combined to create a PSIPave structural index reflective of the pavement responses to primary loads, summarized in Table 5 (8). The segment of Circle Drive eastbound from Faithfull Avenue to Avenue C was omitted because it was comprised of jointed plain concrete pavement and hence not representative of the loading responses of flexible pavement. The PSIPave structural indexes were typically smaller closer to the Circle Drive Bridge, averaging 112 and 95 for the eastbound and westbound directions, respectively. The average PSIPave structural index across all lanes in both directions of travel for the entire segment of Circle Drive was 147, as illustrated in Table 6 and Figure 19, with a coefficient of variance (CV) of 30%.

The resulting PSIPave structural indexes measured on arterial roadways ranged from 49 to 128, typically with the lowest indexes occurring in the curb lanes, as illustrated in Table 5. The mean arterial structural index and CV were calculated to be 80 and 25%, respectively, as shown in Table 6 and Figure 19.

Only one collector roadway was assessed, producing low structural indexes of 32 to 45. Three local roadways were tested, producing structural indexes ranging from 25 to 50, and a mean structural index of 39 with CV of 29%. Since the collector roadway exhibited structural indexes that were congruous with the expected results of a local roadway, its indexes were combined into the local roadway category, thereby creating a new category of roadway (local & collector), with a mean structural index of 39 and CV of 26%.

The local-industrial roadways ranged in index from 117 to 264 and exhibited an average index of 165 and CV of 37%. Due to the wide variety of vehicles and purposes accommodated by local-industrial, they exhibited the greatest range in structural strength of all the tested roadways.

ESALs are a measure of the load response for a rural highway, which is comparable to an urban express or freeway pavement structure. Consequently, the PSIPave Structural Index rating ratio, which takes into consideration both pavement deflections resulting from the application of primary loads and any strengthening or weakening of the pavement materials as a result of the load application (i.e.: strain-hardening), offers a comparative estimate of the probable loading response attainable on various urban road types when utilizing the expressway PSIPave Structural Index rating as a baseline. Since a larger PSIPave structural index equates to a stronger pavement structure, the range of structural index ratios was assessed by inverting the ratio of expressway to road type, as illustrated in Equations 5.1 and 5.2.

$$ESAL\ factor = \frac{SI_{Expressway}}{SI_i} \qquad [5.1]$$

Where:

SI_i = the mean PSIPave structural index obtained under primary loads for road class i, and;

$SI_{Expressway}$ = the mean PSIPave structural index obtained under primary loads for the expressway sample.

$$ESAL\ factor\ range = \frac{SI_{Expressway}}{SI_i \pm 2\sigma_i} \qquad [5.2]$$

Where:

SI_i = the mean peak PSIPave structural index obtained under primary loads for road class i surveyed;

σ_i = the standard deviation of the PSIPave structural index obtained under primary loads for road class i, and;

$SI_{Expressway}$ = the mean PSIPave structural index obtained under primary loads for the expressway sample.

The resulting PSIPave structural index ratios for the various urban roadways using the mean expressway structural index as a baseline are summarized in Table 7 and Figure 20. With the exception of the local-industrial roadway type, the mean PSIPave structural index ratios increased as the roadway classification moved from arterial to local & collector. The increase in ratios was reflective of the typical decrease in pavement structure thickness and/or strength that typically occurs as the roadway classification shifts from arterial to collector and local.

As seen in Figure 20, the greatest range in PSIPave structural index ratio was observed for the local & collector road types. As illustrated in Figure 20, the greatest range in PSIPave structural index ratio was observed for the local & collector road types, followed by local-industrial roadways. The mean structural index of the local-industrial road type was less than the expressway baseline, indicating that on average, these road types typically comprised of pavement structures that were stronger than the expressway structures. However, the maximum range of structural index ratio for this road type reached 3.6, as illustrated in Table 7, thereby indicating that the local-industrial roadways had the potential to be significantly weaker than the expressway pavements, as well.

Combining the PSIPave structural index ratios with the mean GVW ESAL loads for Class 4, 5, 6, 11, 12, 13 and 19 vehicles, as determined in Chapter 4 and measured on the expressway Video WIM site, produced ESAL factors as summarized in Table 8 and Figure 21. As illustrated in Figure 21, the mean GVW ESALs typically increased as the urban road classification moved from expressway to local, with the most significant increase noted for the local & collector roadway type. In contrast, the local-industrial roadways exhibited mean ESAL factors that were typically less than the expressway baseline ESALs, as was indicated in the ratio trends illustrated in Figure 20.

SUMMARY AND CONCLUSIONS

The objective of this research was to evaluate the use of WIM as a tool for collecting traffic load spectra data to establish the framework for generating mechanistic-based ESAL factors representative of typical urban roadway cross-sections.

Upon completion of the Circle Drive Video WIM system reliability validation, it was concluded that the Video WIM system error was somewhat time-dependent in that the six axle semi-trailer error for the westbound curb lane shifted from 1.93% upon initial calibration to -2.45% upon validation, and the error for the eastbound curb lane shifted from 1.38% upon initial calibration to -0.097% upon validation. As such, a daily error factor was calculated for the sample vehicles used to create the load spectra under the assumption that the shift in error was a linear event.

In order to generate a commercial vehicle freeway load spectra that could be utilized to assess the consequences of commercial vehicle loading on different types of urban roadways within Saskatoon, freeway commercial vehicle load spectra was generated utilizing seven consecutive days of traffic data from the Circle Drive Video WIM site, from May 12, 2006 until May 18, 2006. Truck data was collected and classified based on a seventeen category classification system adopted from the Saskatchewan Department of Highways and Transportation.

Analysis of the seven days of data indicated that the majority of the commercial vehicle traffic stream consisted of class 4, 5, 6, 11, 12, 13 and 19 vehicles, which contributed to 96% of the total observed truck population. A total of 16,525 commercial vehicle data records were recorded during the seven day study period. A near 50/50 directional split in traffic was observed, with the majority of the vehicles traveling in the westbound and eastbound curb lanes. As such, only the curb lanes were assessed further to determine the commercial vehicle loading trends that would establish the spectra.

Assessment of the cumulative loads by vehicle class indicated that the majority of the recorded ESALs were contributed by Class 12 and 19 vehicles, followed by Class 5 and 13 vehicles. These findings, with the exception of Class 19 vehicles, correlated with the vehicles masses and presence in the overall observed population. Also, with the exception of Class 4 vehicles, the westbound curb lane was observed to carry the majority of the vehicle population as compared to the other three lanes.

Utilizing a method of ratio comparison between the primary response data of the expressways versus the other urban road types, in conjunction with the ESAL load spectra obtained from the Circle Drive Video WIM site, ESAL factors were calculated by vehicle configuration and road class. The results of this analysis indicated that roadway design utilizing standard ESALs as a method of measuring traffic loading is ill-suited to the pavement structures present in the urban environment. Based on non-linear and deflection primary loading responses, it was concluded that the typical arterial, collector and local roadways present in Saskatoon, Saskatchewan could exhibit 23% to 699% more damage from loading than their expressway counterpart. As such, it is concluded ESAL factors standardized over a dataset of various urban road types should be applied to the typical expressway ESAL in order to obtain more realistic mechanistic-based representations of vehicle loading-induced damages incurred in the urban environment.

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7. ASTM International. Designation: E 1318-02. Standard Specifications for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods.
8. Pavement Scientific International. "City of Saskatoon: 2006 Non-Destructive GPR-HWD Pilot Structural Asset Management Characterization". Project and report conducted for the City of Saskatoon.

Table 1 - Truck Classification System

Class	Vehicle Description/Configuration
4	Straight Truck, 2 Axles
5	Straight Truck, 3 Axles
6	Straight Truck with Tandem Steering
7	Truck and Tandem Pony Trailer
8	Truck and Tridem Pony Trailer
9	Truck and Full Trailer, 5 Axles
10	Truck and Full Trailer, 6 Axles
11	Tractor and Semi-Trailer, 4 Axles
12	Tractor and Semi-Trailer, 5 Axles
13	Tractor and Semi-Trailer, 6 Axles
14	A-C Train, 6 Axles
15	A-C Train, 7 Axles
16	A-C Train, 8 Axles
17	C-Train with Approved Dolly, 8 Axles
18	B-Train, 7 Axles
19	B-Train, 8 Axles
20	B-Train, 9 Axles

Table 2 – Seven Day Analysis Period Count Data (Number of Vehicles)

	Total WB	Total EB	Eastbound		Westbound		Total All Directions	Average Daily Volume
			Lane 1	Lane 2	Lane 3	Lane 4		
Class 4	1216	1,638	1,177	461	208	1008	2,854	408
Class 5	1570	1,628	978	650	296	1274	3,198	457
Class 6	473	87	67	20	34	439	560	80
Class 11	409	318	205	113	74	335	727	104
Class 12	2355	2,155	1544	611	312	2043	4,510	644
Class 13	1161	1,100	702	398	169	992	2,261	323
Class 19	1162	1,253	876	377	156	1006	2,415	345
TOTAL	8,346	8,179	5,549	2,630	1,249	7,097	16,525	2,361
TOTAL	51 %	49 %	68 %	32 %	15 %	85 %	100 %	n/a

Table 3 –Mean Westbound and Eastbound GVW ESALs

	Class 4	Class 5	Class 6	Class 11	Class 12	Class 13	Class 19
WESTBOUND CURB LANE							
Mean	0.831	1.164	0.382	0.373	1.813	1.687	3.380
68th	2.022	2.677	1.972	1.275	3.388	3.149	5.925
95th	3.214	4.191	3.563	2.176	4.964	4.611	8.470
EASTBOUND CURB LANE							
Mean	0.99	1.20	2.46	0.44	1.43	1.71	3.12
68%	2.24	2.37	5.02	1.39	2.72	3.22	5.89
95%	3.48	3.53	7.58	2.34	4.01	4.74	8.67

Table 4 – Westbound and Eastbound Curb Lane Cumulative ESALs

	Class 4	Class 5	Class 6	Class 11	Class 12	Class 13	Class 19	All Classes
WESTBOUND CURB LANE								
Steer Axle	152	845	84	35	764	327	355	2,561
Drive Axle	685	637	84	94	1,514	774	1,138	4,926
Trailer Tridem	-	-	-	-	-	572	800	1,372
GVW	837	1,482	168	156	3,704	1,673	3,401	11,420
Trailer Tandem	-	-	-	27	1,426	-	1,108	2,561
EASTBOUND CURB LANE								
Steer Axle	268	618	88	15	606	248	381	2,224
Drive Axle	903	668	76	68	893	595	968	4,171
Trailer Tridem	-	-	-	-	-	356	690	1,046
Trailer Tandem	-	-	-	7	717	-	694	1,418
GVW	1,171	1,286	165	90	2,215	1,199	2,734	8,860

Table 5 - Urban Roadway PSIPave Structural Indices under Primary Loading

Road Name	Location	Primary Loading SI EB/SB CL	EB/SB ML	WB/NB ML	WB/NB CL
EXPRESSWAY/FREEWAY ROADS					
Circle Drive	N Bridge Abutment to Median Gore	111	113	74	115
	Median Gore Point to Millar Ave	180	115	110	103
	Millar Ave to 1st Ave N	157	146	189	130
	1st Ave N to Faithful Ave	85	171	177	149
	Faithful Ave to E Bridge Abutment	-	-	158	230
	E Bridge Abutment to Ave C	-	-	210	220
	Average	133	136	153	158
ARTERIAL ROADS					
8th Street	Boychuk Dr to McKercher Dr	93	127	98	71
Attridge Dr	McOrmond Dr to Kenderdine Rd	80	75	71	86
	Kenderdine Rd to Berini Dr	58	49	69	49
	Berini Dr to Central Ave	84	79	72	92
Ave C	Circle Dr to 47th St	77	95	128	74
Preston Ave	8th St to Main St	68	-	-	95
	Main St to 14th St	61	-	-	78
	Average	74	85	88	78
LOCAL-INDUSTRIAL ROADS					
Idylwyld Dr Service Rd	60th St to 71st St	264	-	-	264
Edson St	Jasper Ave to Portage Ave	134	-	-	134
Jasper Ave	Melville St to Edson St	146	-	-	146
Portage Ave	Melville St to Edson St	117	-	-	117
	Average	165	-	-	165
LOCAL & COLLECTOR ROADS					
Kenderdine Rd	115th St to Attridge Dr	45	-	-	32
31st St	Ave R to Ave W	50	-	-	50
Adelaide St	McKinnon Ave to Haultain Ave	25	-	-	25
Rylston Rd	Whitney Ave to Ave X	43	-	-	43
	Average	41	-	-	38

Table 6 - Urban Roadway Primary Loading PSIPave Structural Analysis by Road Type

Road Type	Mean PSIPave Structural Index	St. Dev.	CV
Expressway/Freeway	147	45	30%
Arterial	80	20	25%
Local & Collector	39	10	26%
Local-Industrial	165	62	37%

Table 7 - Roadway PSIPave Structural Index Ratios

Roadway	Mean PSIPave SI Ratio	Mean PSIPave SI Ratio - 2 St. Dev.	Mean PSIPave SI Ratio + 2 St. Dev.
Expressway	1.0	1.0	1.0
Arterial	1.8	3.6	1.2
Local-Industrial	0.9	3.6	0.5
Local & Collector	3.8	8.0	2.5

Table 8 - Mean GVW ESAL Factors as per Mean PSIPave Structural Index Ratios

Mean GVW ESALs	Expressway	Arterial	Local-Industrial	Local & Collector
Class 4	0.9	1.7	0.8	3.4
Class 5	1.2	2.2	1.1	4.4
Class 6	1.4	2.6	1.3	5.3
Class 11	0.4	0.7	0.4	1.5
Class 12	1.6	3.0	1.4	6.1
Class 13	1.7	3.1	1.5	6.4
Class 19	3.3	5.9	2.9	12.2

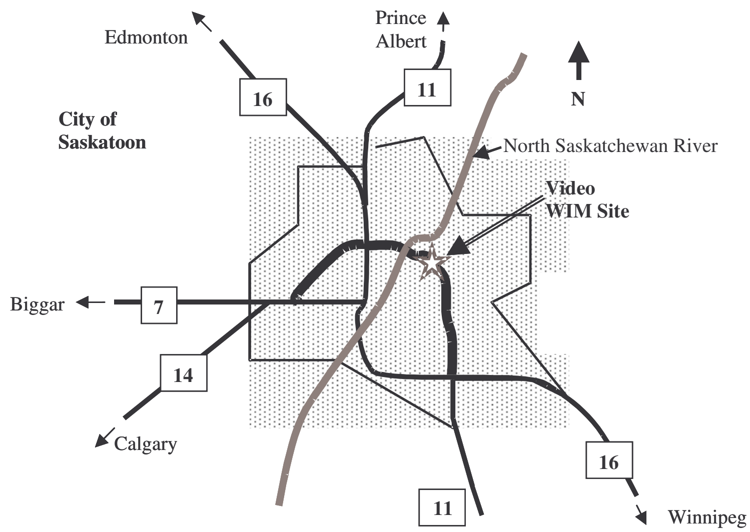

Figure 1 - Circle Drive Video WIM Site

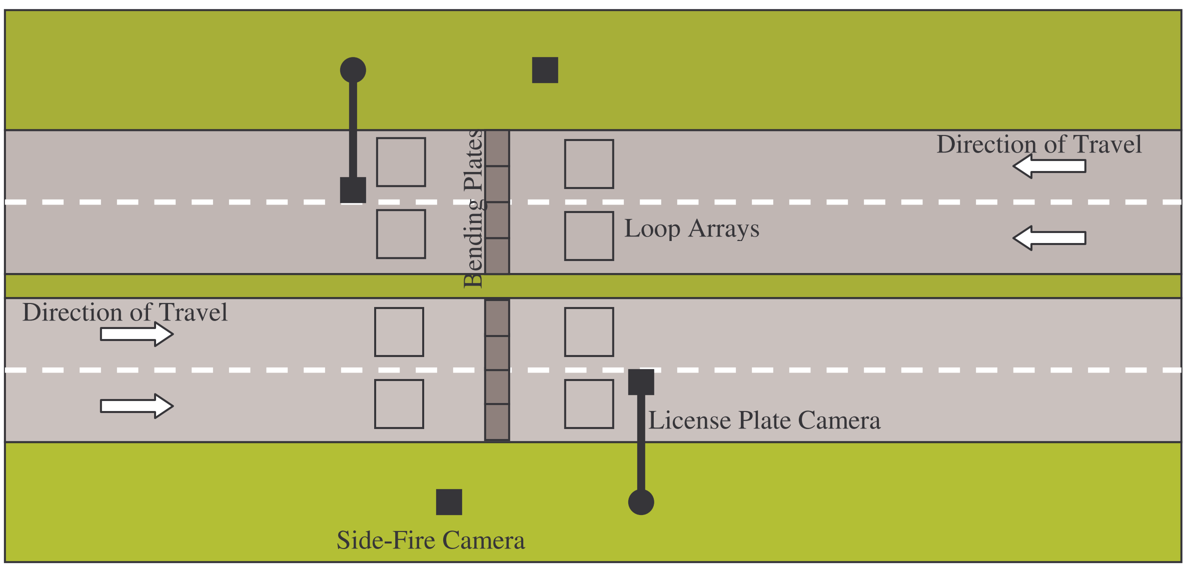

Figure 2 – Schematic of Video WIM Site

Figure 3 - License Plate and Side-Fire Image Vehicle Verification of Validation Trucks

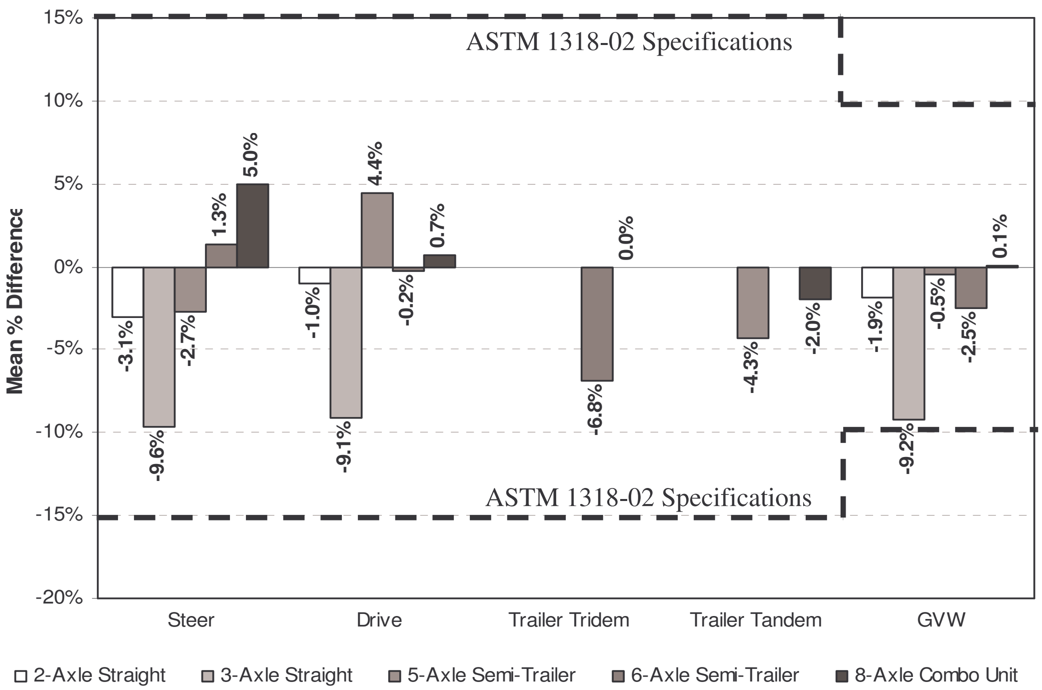

Figure 4 - Westbound Mean Percent Difference across all Vehicle Configurations

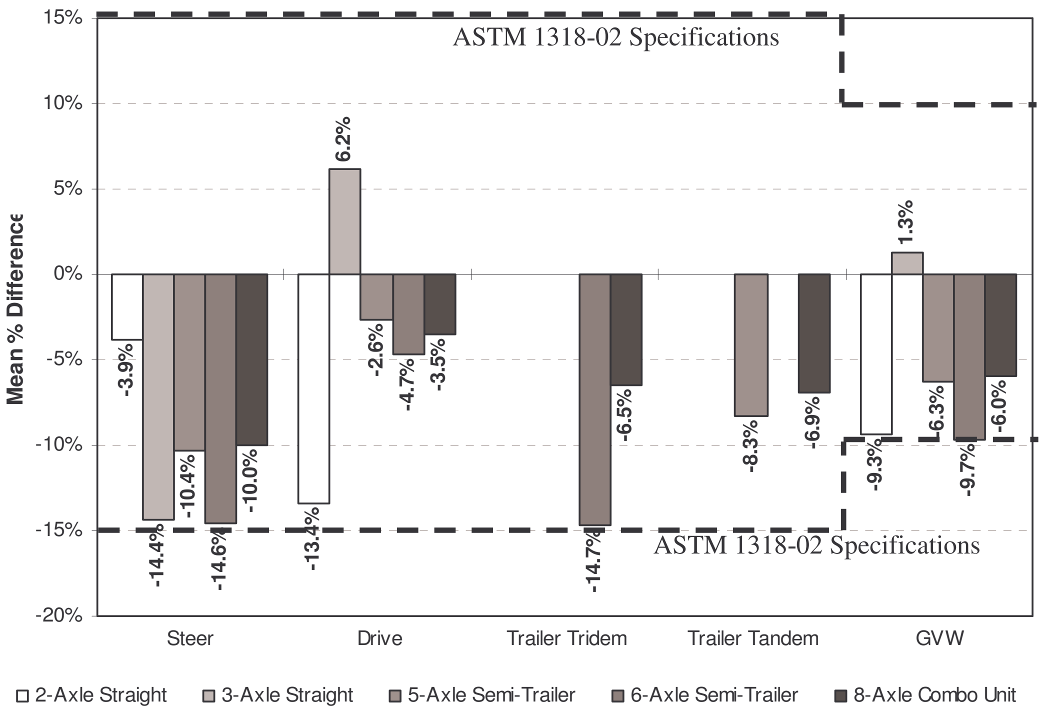

Figure 5 - Eastbound Mean Percent Difference across all Vehicle Configurations

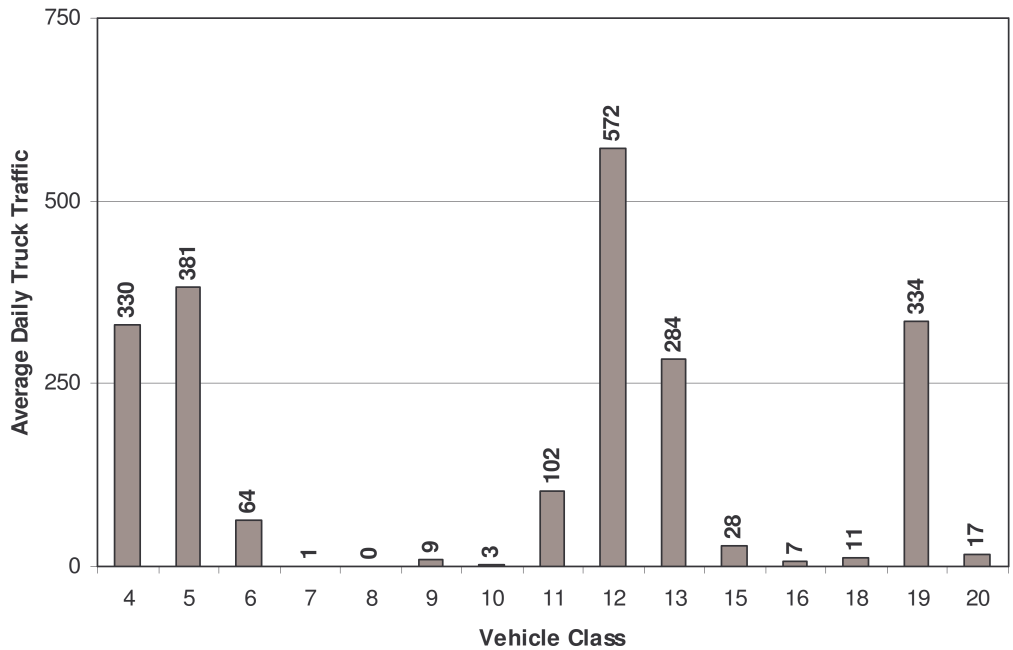

Figure 6 - Distribution of Average Daily Truck Population across all Lanes

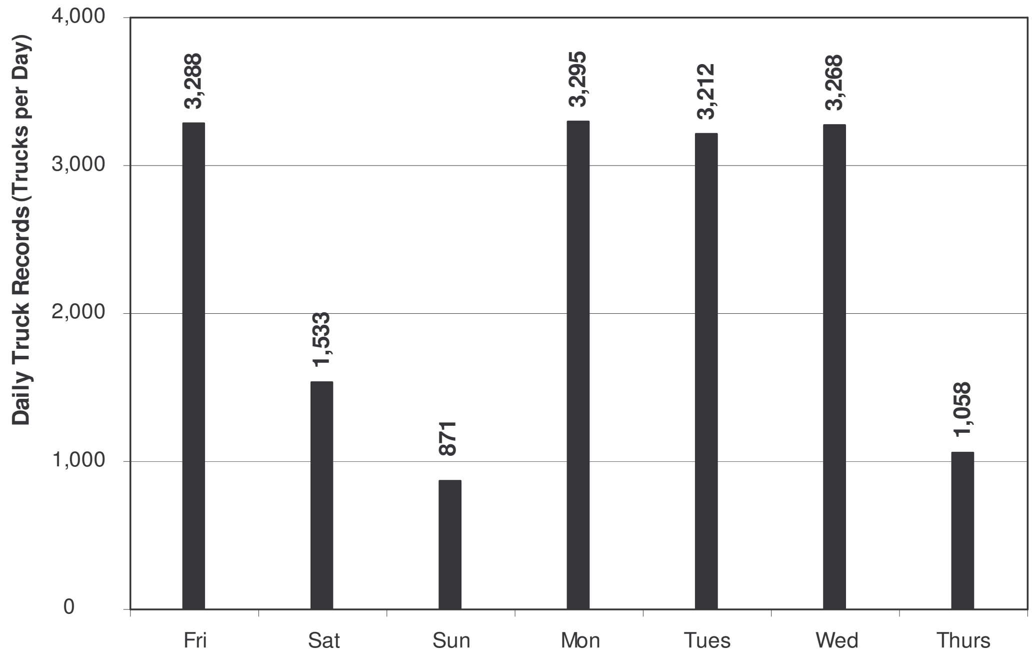

Figure 7 –Individual Truck Traffic Record Analysis

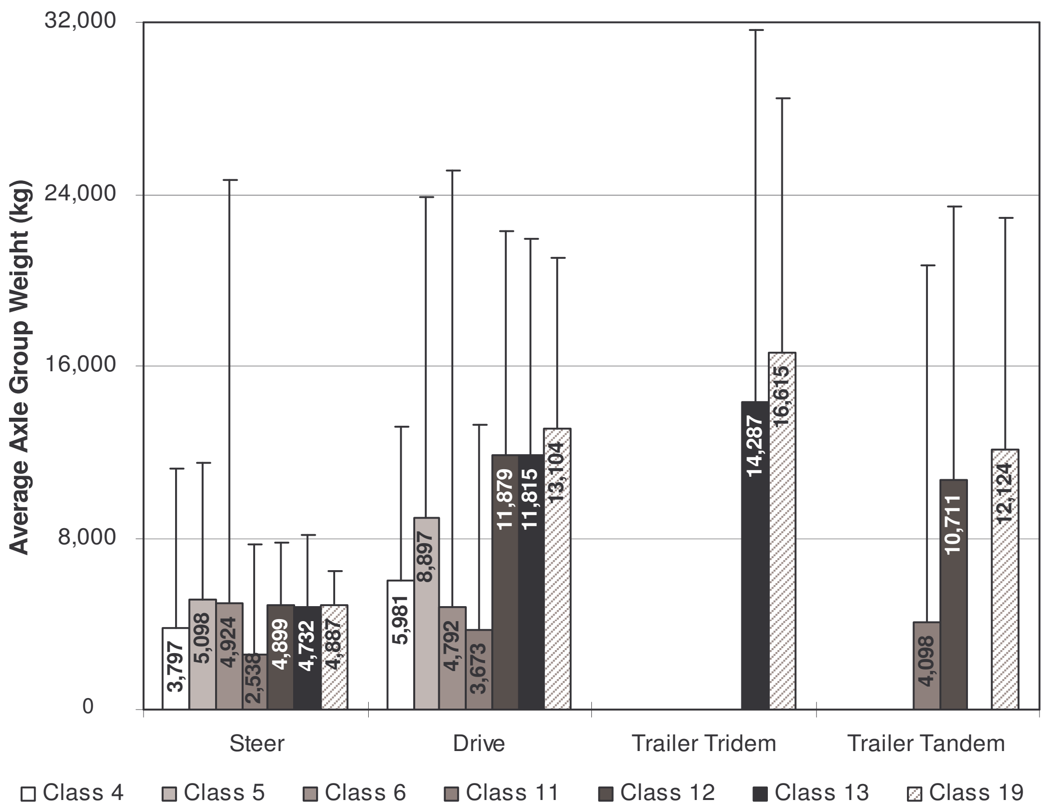

Figure 8 – Average and Maximum Axle Group Weights by Vehicle Class

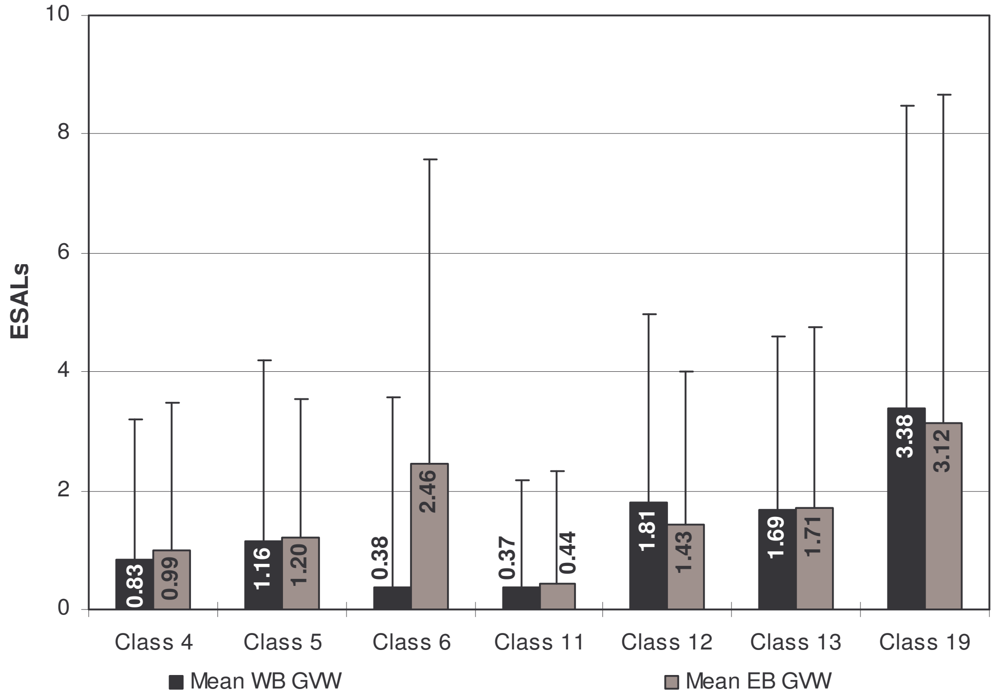

Figure 9 – Mean Westbound and Eastbound GVW ESALs (+ 2 St. Dev.)

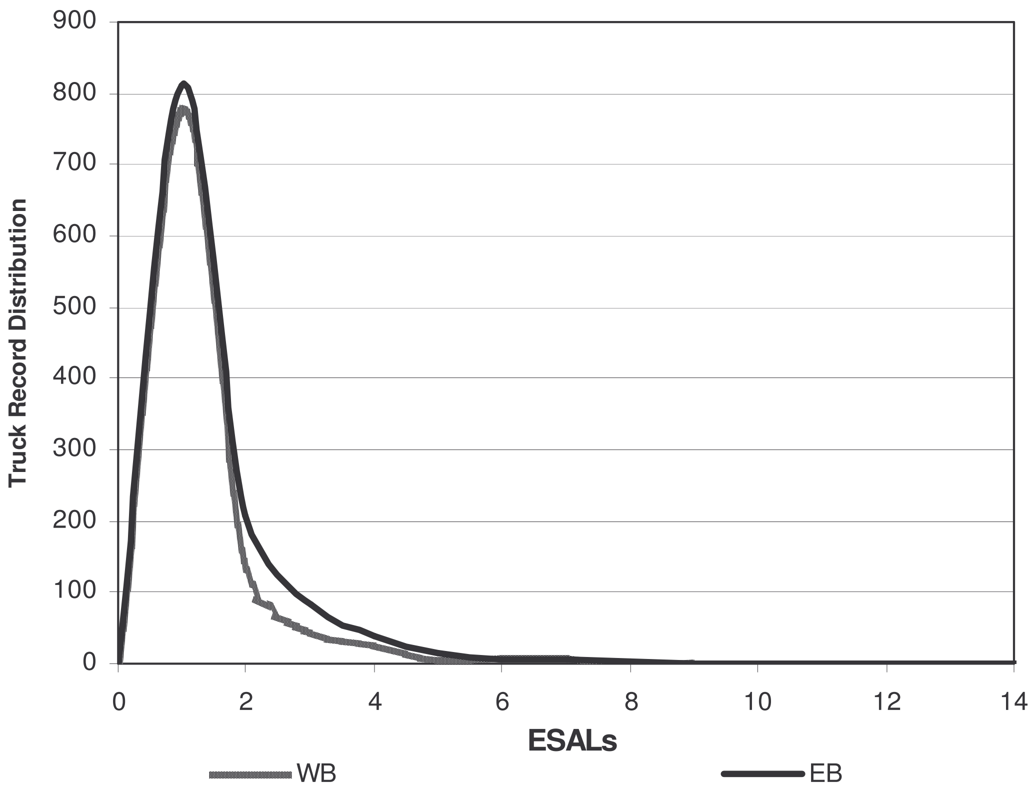

Figure 10 - Cumulative Distribution of ESALs per Class 4 Vehicle

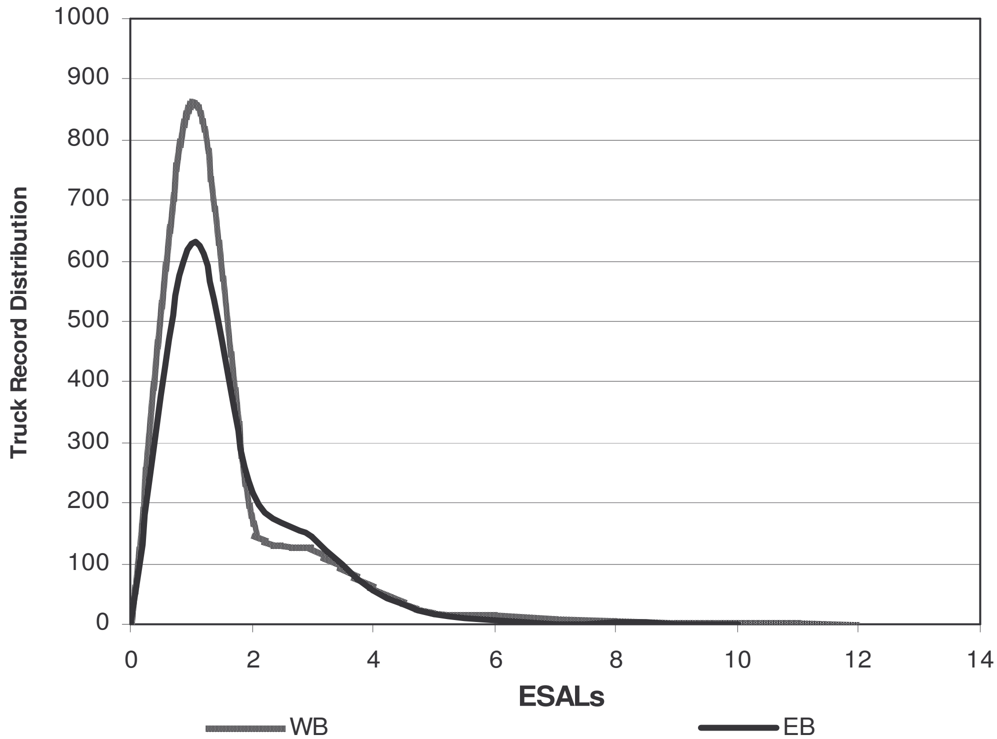

Figure 11 - Cumulative Distribution of ESALs per Class 5 Vehicle

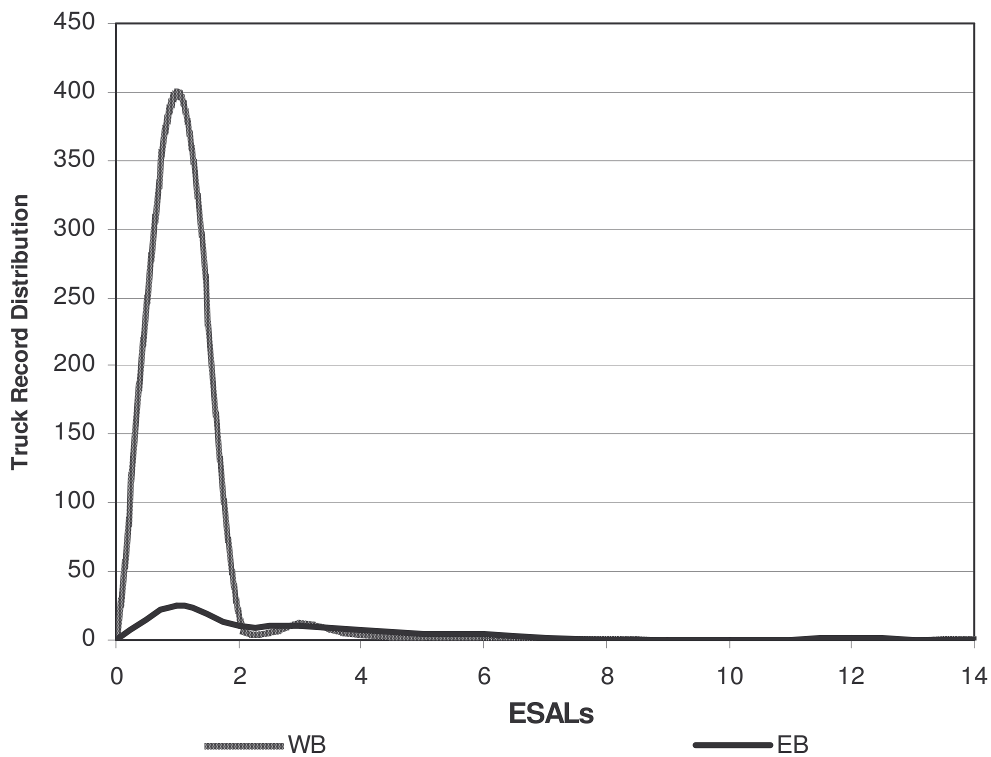

Figure 12 - Cumulative Distribution of ESALs per Class 6 Vehicle

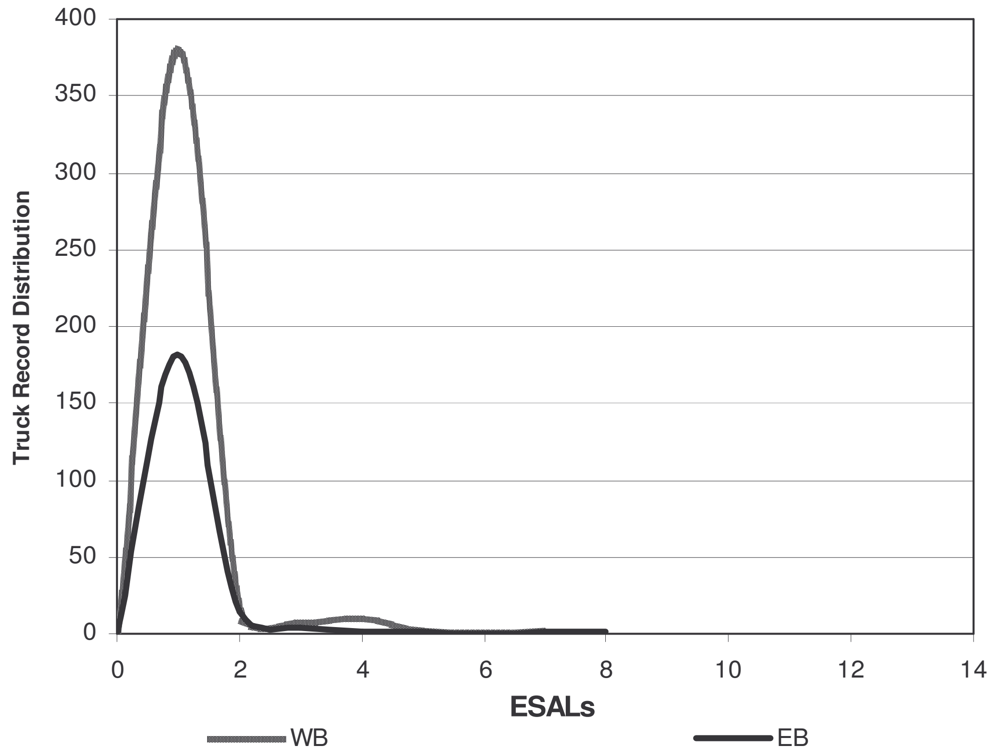

Figure 13 - Cumulative Distribution of ESALs per Class 11 Vehicle

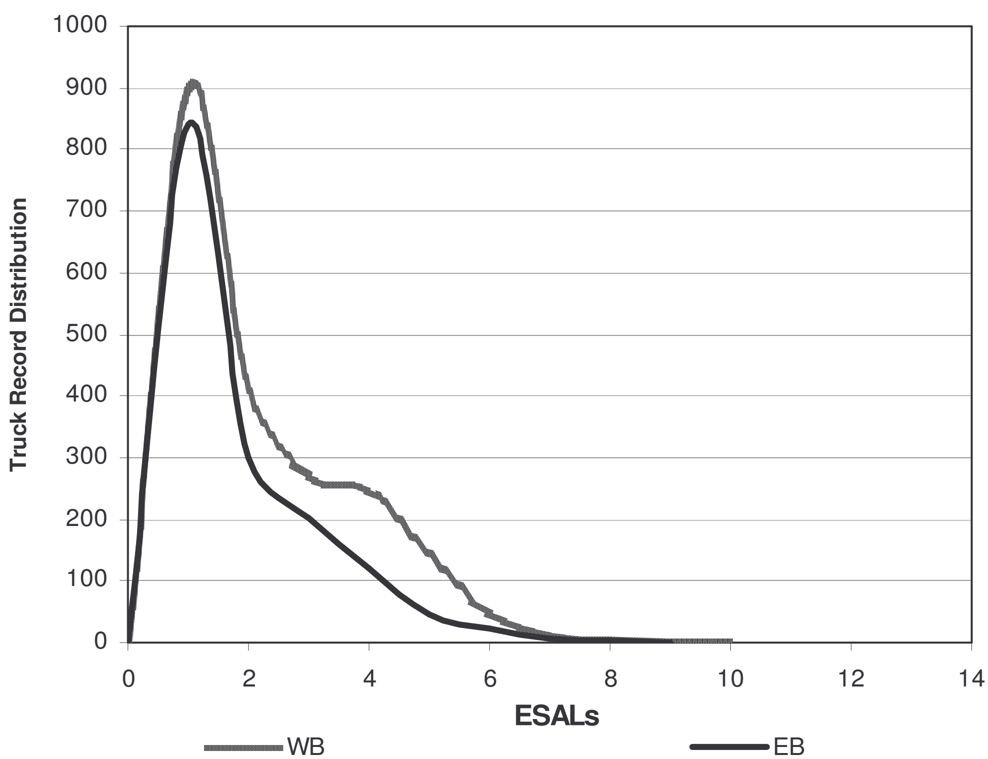

Figure 14 - Cumulative Distribution of ESALs per Class 12 Vehicle

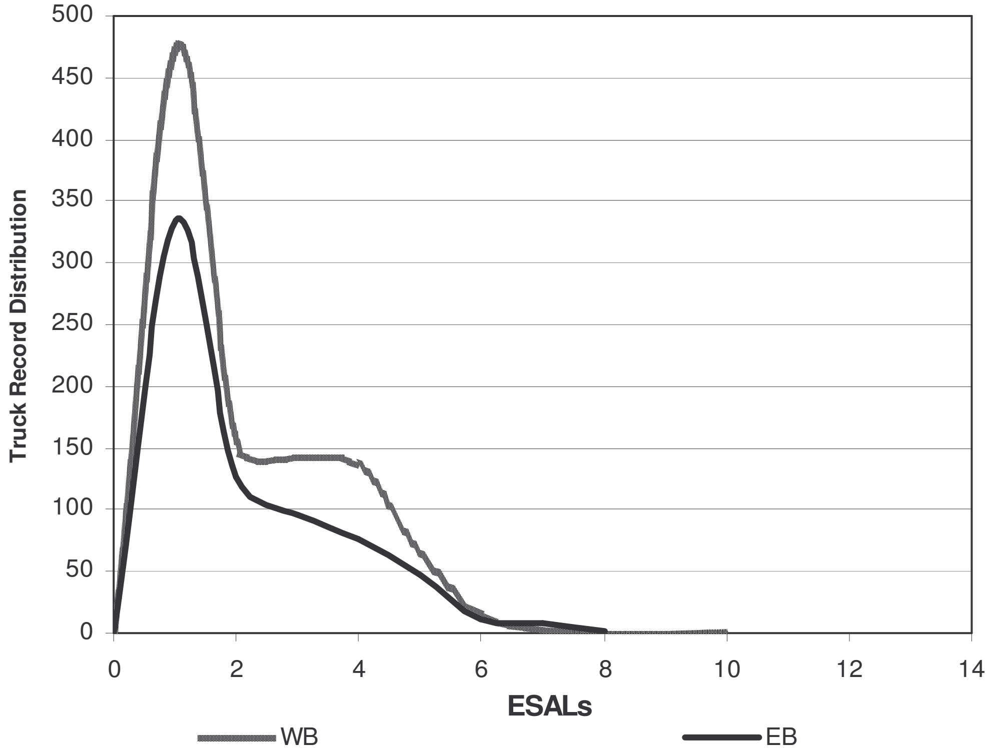

Figure 15 - Cumulative Distribution of ESALs per Class 13 Vehicle

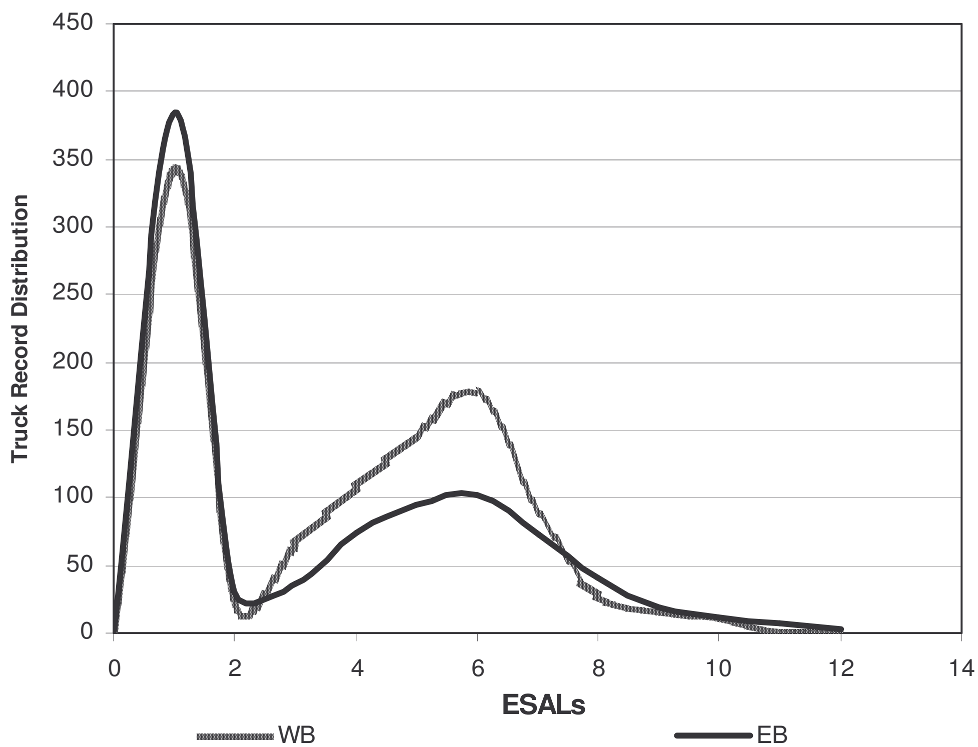

Figure 16 - Cumulative Distribution of ESALs per Class 19 Vehicle

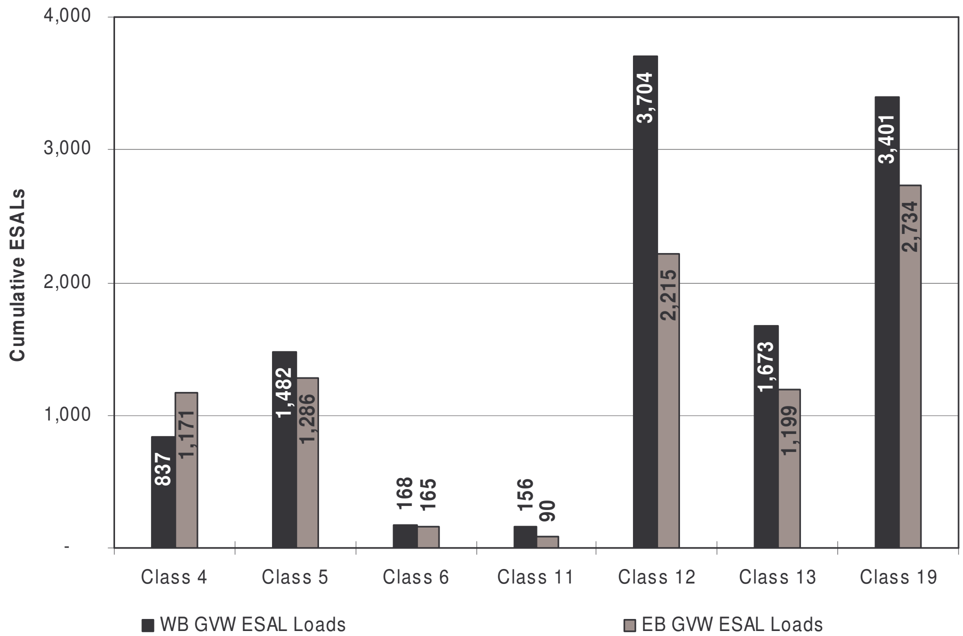

Figure 17 - Cumulative Seven Day ESALs

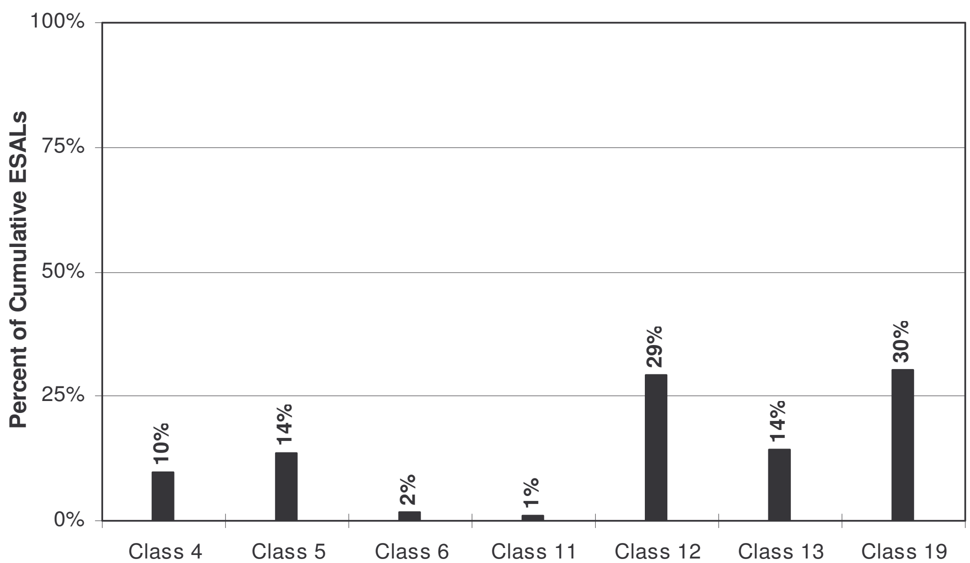

Figure 18 - Cumulative Seven Day Westbound and Eastbound GVW ESALs by Vehicle Configuration

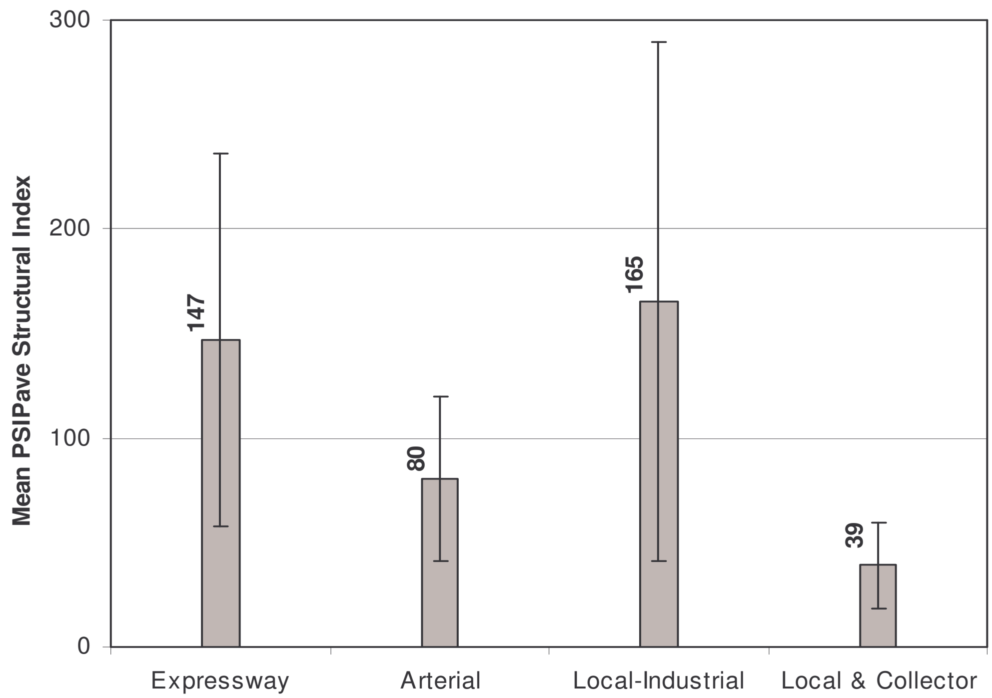

Figure 19 - Mean PSIPave Structural Index by Road Type

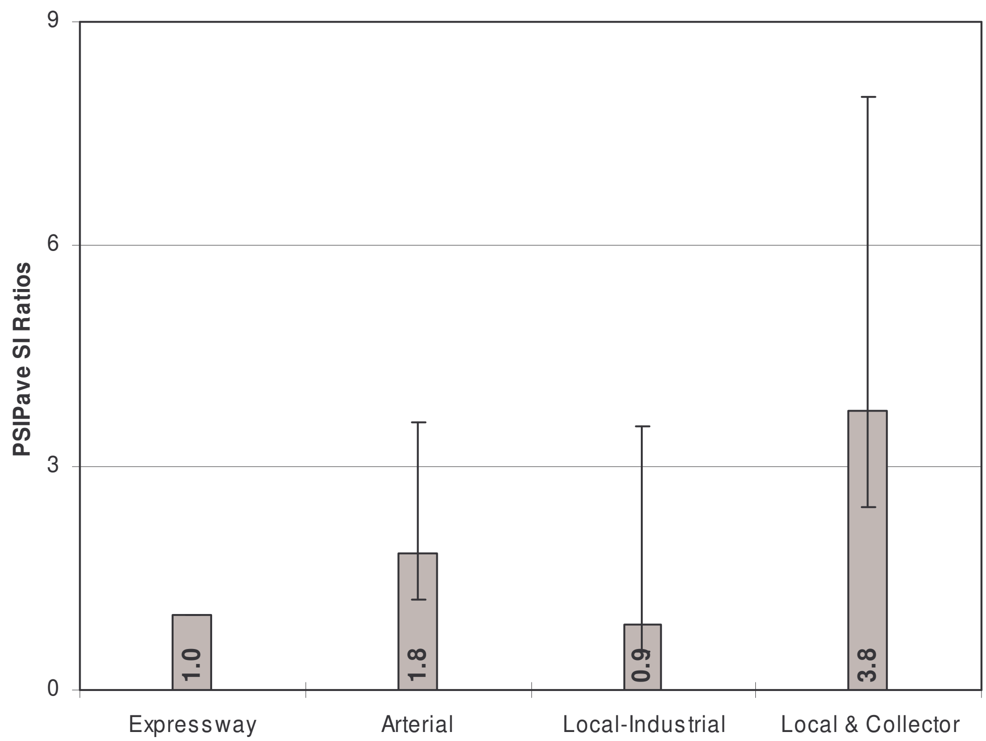

Figure 20 – PSIPave Structural Index Ratios by Urban Road Type (± 2 St. Dev.)

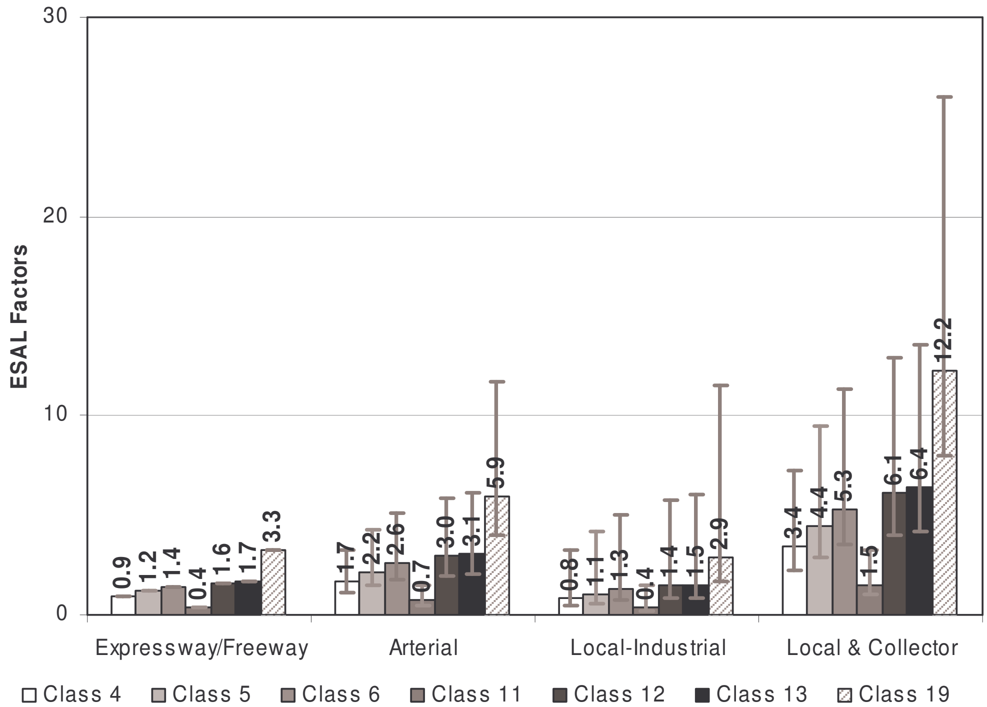

Figure 21 - Mean GVW ESALs as per PSIPave SI Ratio (± 2 St. Dev. PSIPave SI Ratio)