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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

EXAMINE IMPACT TO HIGHWAYS/STRUCTURES – VEHICLES EQUIPPED WITH LIFT AXLES

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16. Abstract

The main objective of this research study is to examine the effects of trucks equipped with lift axles on pavement and bridge structures on Maryland roadways. In this report, the information presented intends to meet the research objectives outlined by SHA. The report discusses Maryland regulations as they compare to other states' lift axle policies. Survey results on a state, national, and international level as well as statistical analyses are displayed to draw conclusions about lift axle policies. The report also discusses theoretical approaches and application to assist in summarizing the effects of lift axles on roads and bridges.

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EXECUTIVE SUMMARY

TITLE: EXAMINE IMPACT TO HIGHWAYS/STRUCTURES – VEHICLES EQUIPPED WITH LIFT AXLES

The health and safety of Maryland's Roads are always a top priority. As the number of heavy trucks on all roads increase, so does the chance for potential damage to Maryland's highway system. There has been increasing interest in lift-axle equipped trucks due to their effect on Maryland highway and bridge structures. Lift-axle equipped trucks are those equipped with additional axles that can be raised or deployed to assist in distributing the weight of the load. These truck configurations are becoming more popular as business continues to grow and cargo sizes increase. However, as technology continues to develop, so do truck configurations. Trucks with two, three and even four lift axles are traveling on highways systems, but there are concerns about the potential for damage due to heavily loaded multi-axle vehicles. These concerns will be discussed later.

In this study, various tasks were completed to gather information on lift-axle equipped trucks and their correlation with various types of damages. Background research was completed in order to review local, national, and even international research and current regulations on gross vehicle weights and lift axle regulations. A survey was sent to all state Departments of Transportation (DOTs) to gather more specific information about policies and practices in each state. One Canadian province also responded to the survey and two other Canadian provinces sent information. Aside from surveys, the Maryland State Highway Administration (SHA) provided truck data from a virtual weigh station (VWS) on MD 32 in Howard Country. After completing proper statistical analysis, theoretical evaluations were completed to measure

potential damage to both bridge structures and pavement. A safety initiative was another component of this project. The research team coordinated with the Maryland State Police (MSP) to develop an inventory from roving crews across the State for one month (2/15/2011–3/20/2011) on the variety in lift-axle equipped trucks. After application of the statistical analysis to the collected data, recommendations and conclusions were proposed.

The survey was sent to all fifty state DOTs, which asked for information on: (1) Vehicle Weight Policies; (2) State Truck Regulations; (3) Deterioration by Trucks; and (4) Lift axle Regulations. There were 28 survey responses from states and one non-survey response as well as one Canadian survey along with two non-survey responses. The survey reveals that most states comply with federally mandated highway regulations especially on their interstate highways. However, for state and local roads, most regulations were not uniform from state to state. Each state typically had its own state regulations for local highways. Overall, what was found from the survey responses is that there is no uniform lift axle regulation.

Data collection was completed via two mechanisms: (1) VWS data and (2) data obtained through the safety initiative with MSP. The virtual weigh station uses weigh-in-motion (WIM) technology to collect real time data on vehicles and stores it in a database on a personal computer. Collected data includes dates and times as well as vehicle characteristics, such as gross weights, axle weights and spacing, and vehicle class type. The safety initiative was a project completed by MSP roving crews. The roving crews collected data from various truck types on the roads near weigh stations. The data that was collected consisted of vehicle type, axle weights, and compliance with the laws and regulations.

These two sets of data were collected for inventory and a statistically-determined nominal truck was determined from filtering the data to focus specifically on dump service vehicles (four-axle dump trucks with one lift axle). With the nominal truck configuration, applicable methods that examine deck behavior, girder behavior, and pavement damage can be employed to determine potential damage to a highway system. More specifically, shear analysis of bridge decks, moment analysis for the bridge girders, and pavement damage analysis was all completed to determine the impact of lift-axle equipped vehicles. From the VWS data, month-to-month statistics on overweight and compliancy was also gathered. For the safety initiative, inventory was collected over a month that shows overweight and compliancy to laws.

After reviewing the results of the statistical analysis as well as theoretical application, conclusions and recommendations were made. In the VWS statistical analysis it was found that the highest number of overweight trucks traveled during the summer months. Also, there was no relationship between overweight trucks and lift axle weights where the lift axle is either below Maryland's mandated restriction, compliant with the weight restriction or exceeding the restriction. However, there is no pattern for these instances. This is furthermore confirmed through the findings of the safety initiative which revealed that the largest violation for dump service vehicles were those that had improper down force pressure on the lift axle. The dump truck with the fourth lift axle raised (tandem-axle case) induced 1.32 times more shear damage on the bridge deck than that of a truck with the axle deployed (tridem-axle case) carrying the same gross weight. As for the moment analysis of the bridge girders, the biggest difference between tandem- and tridem-axle trucks was on small span bridges less than 20 feet. The pavement analysis showed that for the truck with the lift axle raised, the damage is about three times as great as the damage of a tridem-axle (deployed) case. Overall, the lift axle does play a pertinent part in the impact of truck weights on highway infrastructure. Also, more consideration of multi lift axle equipped vehicles should be investigated in order to make final recommendations for regulation of lift-axle equipped vehicles. Making truck companies accountable for violations and increasing the penalties for those who violate the lift-axle regulations could help enhance highway infrastructure assets (i.e., enforcement of lift axle policy even if the lift axle weight is below the mandated weight). Overall, in order to make a thorough conclusion on lift axle impacts, more research should be completed that encompasses more truck configurations.

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Chapter 1: Introduction

1.1 Background

On today's highway network, there is an abundance of lift-axle equipped vehicles. The rise in this new innovative source of technology has been a large benefit to companies, allowing them to increase Gross Vehicle Weight (GVW) while still meeting the Federal Bridge Formula (FBF) requirements. While the use of lift axles allows trucks to carry more weight and assist in distributing it equally, there is concern that the additional weight may pose a threat to roads and bridges.

Vehicles equipped with lift axles are often found to be over the allowable weight limits. Aside from overweight vehicles, the non-engaged lift axle of fully loaded vehicles also presents concerns. If the driver raises the lift axle and neglects to re-deploy it as required by the regulations, this adds additional weight to the back tandem axles. Essentially, this has the potential to cause substantial damage to both pavement and bridge structures over time.

Currently, in Maryland, there are several regulations in reference to lift axle equipped vehicles. The Code of Maryland Regulations (COMAR) provides minimal down force pressure when the lift axle is engaged with the pavement. However, there are no regulations applied to non-Maryland registered dump service vehicles (DSVs) that are equipped with lift axles. With regard to a Maryland registered DSV, there are no concerns with enforcement as long as GVW meets the requirements specified in both the Maryland Annotated Code and COMAR when weighed. However, there is an enforcement issue involving vehicles equipped with multiple lift axles. If the roving crews do not have the proper number of portable scales to weigh a vehicle larger than a four-axle dump truck and if the crew is not within ten miles of a static weigh station, Maryland law prohibits law enforcement from requiring the vehicle to travel to a weigh station. Under these circumstances, law enforcement is not able to weigh the vehicle simply because they do not have enough portable scales to effectively weigh a vehicle equipped with multiple lift axles.

Overall, there are not only concerns with potential damage to pavement and bridge structures, but also concerns with regulations and enforcement. This report examines the concerns related to damage of infrastructure as well as with limited regulation and policy on lift axle usage. This report is also backed by data collection and analysis that will assist in summarizing the concerns with lift axles.

1.2 Research Objectives & Scope of Work

In order to completely investigate the effects of lift-axle equipped trucks, the following research objectives were identified:

- Locate, assemble and document other states' requirements and concerns for lift-axle equipped vehicles;
- Identify what other states are doing to examine the effects of lift axles and what methods are being employed to solve them;
- Identify current or on-going research that may be underway nationally regarding this issue;
- Coordinate with enforcement to produce data derived from enforcement initiatives/spot checks;
- Organize, evaluate, and document the information acquired and produce a final report assessing the project; and
- If it is determined that this is a significant problem; examine and identify countermeasures which could include seeking legislation instituting mandated down-force pressure requirements for multiple lift axle equipped vehicles operating in Maryland.

In this report, the information presented intends to meet the above objectives outlined by SHA. The report discusses Maryland regulations as they compare to other states' lift axle policies. Survey results on a state, national, and international level as well as statistical analyses are displayed to draw conclusions about lift axle policies. The report also discusses theoretical approaches and application to assist in summarizing the effects of lift axles on roads and bridges.

1.3 Research Approach

The following four tasks describe research strategies developed for this project:

Task 1: *Collect and Study the State-of-the-Art and State-of-the-Practice Methods in Federal and State Agencies, the Trucking Industry and Research Community*

In this task, the following issues were identified. In Maryland, the Annotated Code, and COMAR cover four-axle DSVs that are equipped with lift axles, but do not regulate any other vehicle equipped with lift axles. Further, it does not address vehicles that may be equipped with multiple lift axles. Maryland is also experiencing four-axle DSVs raising the lift axle before going through toll booths, which reduces the toll they are required to pay. Aside from these concerns, there are also concerns about proper down force pressure that should be applied to the lift axle. While the law and regulations address four-axle dump service vehicles, there are no requirements that address other types of lift-axle equipped vehicles.

The focus in this task was to locate, collect and list all the available current state-of-the-practice methods for: (1) The Federal Highway Administration's (FHWA) regulations covering lift-axle equipped vehicles; (2) other states' laws and regulations covering lift-axle equipped vehicles; (3) vehicles and combinations with lift axles by the truck industry; and (4) all types of lift-axle equipped vehicles using Maryland's highways. A literature search on this issue was conducted by reviewing material published by the Transportation Research Board (TRB), American Society of Civil Engineers (ASCE), Transportation Research Information Services

(TRIS), National Technical Information Service (NTIS), Transportation Research Laboratory (TRL) and other states. The research team also searched historical Maryland regulations to examine the history of Maryland-registered DSVs.

The literature review also addressed additional issues associated with lift-axle equipped vehicles beyond laws and regulations, which include: (1) lift-axle equipped vehicle design and use; (2) highway safety considerations; (3) vehicle, pavement and bridge damage considerations; and (4) economic considerations.

Task 2: *Survey Other States to Identify Key Practices and Regulations on Lift-axle equipped Vehicle*

A survey was sent out through the American Association of State Highway and Transportation Officials (AASHTO), Commercial Vehicle Safety Alliance (CVSA) and other channels to gather information on lift axle regulations by the research team. The survey examines regulations covering lift-axle equipped vehicles and enforcement of state registered and foreign vehicles. The survey requests information on: (1) vehicle weight policies; (2) state truck regulations; (3) deterioration of roads and bridges by trucks; and (4) lift axle regulations. The survey discussed permit or approval requirements, weight specifications other than the FBF, equipment and truck specifications. Also in the survey are questions relevant to Maryland's current law of covering only four-axle dump service vehicles. From this survey, information was gathered in reference to the absence of lift axle regulations in other states and the research team was able to identify what states are doing to examine this problem as well as what methods are being employed to solve them.

Task 3: *Identify Types of Lift-axle Equipped Vehicles Manufactured and which Types are used on Maryland Highways*

During the study period, the MSP and Maryland Transportation Authority police (MDTAP) were interviewed for their technical input and to provide enforcement data. In the safety initiative, collected items included those fully loaded vehicle operating with lift axle not engaged, improper weight on lift axles, insufficient air pressure for lift axles, lift-axle equipped vehicles raising the axle at toll booths to avoid paying a higher toll for total axles, instances where enforcement encounters multiple lift-axle equipped vehicles and is not able to weigh them with portable scales because of not having enough portable scales to weigh it, etc. During the study period, the research team coordinated with MSP by having random special enforcement initiatives/spot checks to document the extent of the problem. Digital data was gathered from the MD 32 virtual weigh station (VWS) site. The VWS was able to capture one year of data including all classes and combinations of vehicles. The collected information included fully loaded vehicles operating with lift axle not engaged, over the gross vehicle weight limits, improper weight on lift axles, as well as vehicles using insufficient air-pressure for lift axles. The statistical approaches were then applied to the digital data from both methods of collection. Appropriate statistical analysis was completed for the best display of results.

Task 4: *Conclusions and Future Research*

Literature and survey results gathered from federal, state and in-state agencies have been summarized and analyzed. The summary addresses whether Maryland should implement regulations covering non-dump service vehicles and combinations that are equipped with single or multiple lift axles. It also addresses advantages to allowing vehicles equipped with multiple lift axles on our highways, e.g., economic, increased productivity and efficiency, reduced pavement wear/stress, etc. This report further discusses the effect of these lift-axle equipped trucks on bridge structures. The research team has organized, evaluated, and documented the information acquired and produced a final report assessing the project. This includes identifying advantages, disadvantages, areas of concern, etc. Conclusions and future research needs have been determined and summarized based on the information collected.

Chapter 2: Literature Review

2.1 Lift Axle Usage

The purpose of a lift axle is to provide additional support when a truck is carrying a load that is heavier than was originally intended. Lift axles allow a truck to carry greater payloads or cargo for a small increase in vehicle cost. Lift axles can be raised or lowered based on the weight being carried. Specifically, a lift axle is an additional axle located on the truck and has the ability to be raised or lowered based on the GVW or the weight of cargo (Figure 2-1). Most automatic lift axle systems are operated by the usage of a hydraulic or air pressure bag technology in the axle configuration, which regulates the lowering of the lift axle. The increase in down-force pressure on the valve for the lift axle signals the lift axle to be lowered and it assists in the total distribution of the GVW. In a manual lift axle system, the lowering of the lift axle is controlled by the vehicle operator. Drawbacks to the usage of lift axles were identified in the National Cooperative Highway Research Program (NCHRP) Report 575 (Sivakumar 2007) include:

- Lift axles, when deployed, reduce the turning capabilities of the truck and may cause the truck to jackknife on slippery roads. If the axles are raised through the turn the truck's stability is compromised and the chance of rollover is increased.
- The proportion of the load carried by the lift axle is often controlled by the driver. If the axle is deployed too far, it may carry too much of the load. If the axle is not deployed far enough, the other axles may be overloaded.
- Enforcing compliance with lift axle regulations is very difficult. Lowering retractable axles when approaching a weigh facility and then raising the lift axles after clearing the

weigh facility is not uncommon. Regulatory agencies sometimes require the controls for raising and lowering the lift axles to be located outside the cab to inhibit this practice. Some states have banned the use of lift (or retractable) axles for the reasons cited above.

Figure 2-1 Four-axle Dump Truck with Lift Axle (L) and
Seven-axle Truck with Triple Lift Axles with a Tag-Along (R)

(Ref: maxleairride.com)

There is a variety of control systems for lift axles. The lift axle can have a switch on the interior of the cab where the driver determines when the lift axle is raised or lowered. This same switch could also be on the exterior of the cab, but in most applications, it is located inside the cab of the vehicle. Also, another common option is having the deployment switch on the interior and the regulating switch on the outside. This simply means that the driver controls the lift axle when it is down but cannot control it when it rises (due to less cargo) from the interior of the cab. In other words, the driver can only turn it on or off inside. The ability to regulate the pressure is done on the outside.

Vehicle steering is also a concern with lift-axle equipped trucks. Some axles are non-steerable where steering around corners and on curves becomes difficult. The only way to ease maneuverability would be to raise the non-steerable axle when turning. However, when lifting the axle to steer around corners or turns, this increases the likelihood of pavement damage because the lift axle weight is then shifted to the other fixed axles. There are also self-steering axles that allow the wheels to dictate or steer based on forces between the tires and the road surface. This essentially creates less potential for pavement wear. Self-steering axles have various load capacities and specifications. While most lift axles operate with single tires, some are equipped with dual tires. However, these applications are rare (Koehne and Mahoney 1994).

2.2 Lift Axle Manufacturers

As lift axle usage increases, so does the lift axle technology. There are plenty of different combinations and configurations of trucks that use lift axles, but manufacturers work to produce state-of-the-art and up-to-date equipment. As mentioned in the previous section, the key to the lift axle is its control system. Issues arise with the location of the control system as well as who operates the control device. Some states place regulations on the control device, whether it is an automatic device that operates the lift axle based on the gross weight of the truck or if the driver manually controls the lowering of the axle. Regardless of whether the control system is automatic or manual control, there are two types of suspension systems: air pressure or hydraulic suspension as well as steel leaf spring suspension. This research shows that more manufacturers are moving toward air pressure suspension.

New lift axle technology developments are moving toward self-steering air suspension configurations. Haldex, a manufacturer known for work in suspension systems, has created a new air suspension automatic control valve that assists in the activation of the lift axle based on the weight of the load. This system also works for trucks with multiple lift-axles. Aside from the automated control, the control valve can also be controlled manually if need be, thus giving the driver the ability to activate the lift axle if and when appropriate. However, many lift axles do still use the leaf spring system. Hendrickson, another popular manufacturer, is working on a new lift axle series, the Composilite SC Series (shown in Figure 2-2), which reduces system weight and minimizes the package space. This lowers the gross weight of the vehicle. The new series will provide a 20,000-pound capacity for new lift axles. This is significant because other versions of Hendrickson's lift axles only allow capacities of up to 10,000 and 13,500 pounds.

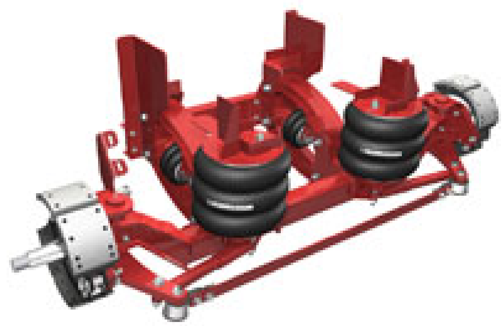


Figure 2-2 Hendrickson Composilite SC20
(http://www.hendrickson-intl.com)

Overall, there is new technology that is moving towards self-steering, which is typically better for reducing potential road damage. It is also evident that older technology is still being used and enhanced. Nevertheless, whether a lift axle uses a steel leaf spring system or and air suspension system, lift axle technology continues to progress.

2.3 National Policies

On a national level, the American Association of State Highway and Transportation Officials (AASHTO) has conducted research on legal truck loads and their effects on U.S. highways. The FBF is a law that limits GVWs and axle weights for overall protection of the highways and bridge structures. The FBF calculates the maximum allowable load (the total gross weight in pounds) that can legally be imposed on the bridge by any group of two or more consecutive axles on a vehicle or combination of vehicles.

The FBF is given as follows:

$$W = 500[\left(\frac{LN}{N-1}\right) + 12N + 36] \qquad \text{Equation 2-1}$$

Where,

W= the overall gross weight in pounds that can be carried on any group of two or more consecutive axles to the nearest 500 lbs,

L = the distance in feet between the outer axles of any two or more consecutive axles, and

N = the number of axles being considered.

The Federal-Aid Highway Act of 1956, otherwise known as the National Interstate and Defense Highways Act, put limits on vehicle weights to protect the federal investment and to protect bridges. A maximum gross weight limit of 73,200 pounds was established along with 18,000 pounds on single axles and 32,000 pounds on tandem axles (Congressional Budget Office). The Federal Aid Highway Amendments of 1974 (signed into law in 1975) established the Federal Bridge Formula as law and provided for the maximum gross weight of 80,000 pounds. However, some states were allowed to maintain, or grandfather, their local truck weights. More specifically, lift axles are used on more than 70% of all four-axle single-unit trucks (Sidvakumar, 2007), which is a popular type of truck in Maryland. Additionally, as indicated in NCHRP Report 575, AASHTO recommended the following basis for lift-axle equipped vehicles:

- All controls must be located outside of and be inaccessible from the driver's compartment.
- The gross axle rating of the devices must conform to the expected loading of the suspension and shall in no case be less than 9,000 pounds.

- Axles of all retractable devices manufactured or mounted on a vehicle after January 1, 1990 shall be engineered to be self-steering in a manner that will guide or direct the mounted wheels through a turning movement without the tire scrubbing or pavement scuffing.
- Tires in use on all such axles shall conform to load capacities with relevant State regulations or with Federal Motor Vehicle Safety Standards (FMVSS) or with both as is deemed appropriate. (Sidvakumar, et al 2007)

A national survey from NCHRP Report 575 was also completed and asked states about their local policies as they pertain to axle weight limits. The results can be found in Appendix A of Report 575. The survey also asked about hauling exemptions and permits related to weight tolerances for possible overweight axles (Appendix A). The survey results (Table 2-1) showed the axle weight limits for single tandem-, tridem- and quadrum-axle configurations and included questions about lift axle regulations. The results are as follows:

Survey Questions on Lift Axles	*DOT Responses*		
	Yes	No	Not Sure
Question 4.1: Does your agency permit the use of liftable axles on heavy trucks?	41	3	
Question 4.2: Do any of the state legal loads used by your agency represent trucks with liftable axles?	14	28	
Question 4.3: Does your agency or state monitor the weight carried by the liftable axles to ensure compliance with state regulations?	21	5	5
Question 4.4: When performing load ratings for trucks with liftable axles, are ratings checked with the axles in the raised position under full load?	3	15	

Table 2-1 Lift Axle Survey Results by NCHRP Report 575 (2007)

According to Report 575, nationally, state regulations vary greatly for lift axles weighing protocol as well as in monitoring weight and compliance. The report also examined posting loads with FBF. Posting loads are a subset of the state or federal legal loads used for implementing bridge weight restrictions. (Sidvakumar, et al 2007) There were several posting loads which complied with the FBF gross weight limits, but neglected to satisfy or exceeded the FBF limit for axle groups or the federal single axle limit of 20,000 pounds.

2.4 International Policies

On an international level, Canada has a lot of experience in lift-axle equipped trucks. Canadian truck policies are indeed different as they have higher GVWs and allow lift axles of various configurations (See Chapter 3 for Canadian Policies).

For single unit vehicles, the gross weights are as follows:

- For a two-axle vehicle, 14,000 kilograms (30,864.4 pounds)
- For a four-axle vehicle, 25,000 kilograms (55,115 pounds)

For three-axle vehicles, there are special provisions outlined in Table 2-2.

Rear Axle Spacing (Meters)	**Maximum Allowable Gross Vehicle Weight (Kilograms)**
1.0 to less than 1.2 (3.28 - 3.936 ft)	20,000 (44 092.4524 lbs)
1.2 to less than 1.3 (3.936 – 4.264 ft)	21,500 (47398.9 lbs)
1.3 to less than 1.4 (4.264 - 4.592ft)	22,000 (48501.2 lbs)
1.4 to less than 1.5 (4.592 – 4.92 ft)	22,300 (49162.58 lbs)
1.5 to less than 1.6 (4.92 – 5.25 ft)	22,500 (49603.5 lbs)
1.6 to less than 1.7 (5.25 – 5.57 ft)	23,000 (50705.8 lbs)
1.7 to less than 1.8 (5.57 – 5.90 ft)	23,500 (51808.1 lbs)
1.8 or more (5.9 ft)	24,000 (52910.4 lbs)

Table 2-2 Three-Axle Truck Weight Provisions

Because Canada has experience with lift-axle equipped vehicles, various provinces have created laws, policies and initiatives to regulate their usage. Lift axles are not only popular on dump service trucks, but on five- and six-axle vehicles as well. As such, lift axle regulations do not just apply for dump service vehicles.

Ontario, for example, has the following lift axle regulations:

- The tractor must not be equipped with or have controls, whether remote or manual, that would allow the driver to lift or deploy the self-steering axles of the semi-trailer or to alter the weight on the self-steering axles except for manual controls or for automatic controls that activate only when the combination is reversing.

- The tractor must not be equipped with or have any controls that would allow the driver to lift, deploy or alter the weight of the tridem axle of the lead trailer other than manual controls that would allow the driver to alter the weight on the forward axle of the lead trailer's tridem axle, but only if,
  - the controls do not activate unless the emergency 4-way flashers are activated; and
  - the controls contain a device that prevents altering the axle weight when the combination is travelling at a speed over 60 kilometers per hour.

Ontario has made strong provisions to take control of the lift axle away from the driver, so the lift axle is raised and deployed based on the weight applied as well as on other conditions. Because of the increasing popularity of lift axles, Ontario has put together a new initiative called Safe, Productive, Infrastructure-Friendly (SPIF) vehicles. This initiative was created to be as productive as possible while ensuring vehicle performance characteristics meet or exceed Canadian guidelines and that heavy truck damage to roads and bridges is minimized. Through this initiative, regulations have been modified and truck configurations and criteria have been outlined to get vehicles SPIF-ready and integrate new policies into existing vehicles on Ontario roads. SPIF vehicle regulations ensure safe maneuvers of multi-axle vehicles and must be equipped with self-steering axles and load-equalization tools. The Ministry of Transportation in Canada has determined that there is no longer a need to apply special restrictive weights to aggregate vehicles that meet the SPIF standards. Calculating the allowable gross weight of SPIF vehicles is the same regardless of the product being carried.

Chapter 3: Theoretical Review

3.1 Structural Capacities Based on Failure Modes

As mentioned in the previous section, U.S. and the various state regulations are based on the FBF, which is a law that limits GVW for overall protection of highway and bridge structures. The guideline followed by the developers of the FBF was that a typical HS20-rated bridge would not be overstressed by more than five percent by the weight of the typical combination truck with one trailer (as shown in Figure 3-1 for AASHTO Standard design truck HS20). The concept of the FBF evolved over half a century and it went through several revisions. The analyses conducted in developing Bridge Formula B of the FBF considered only simply supported superstructures, but it is considered representative of a variety of supported structures and the resulting formula was generally applicable to all cases. As such, it can be stated that the policy was based on the capacities of the bridges. In this section, there is more discussion of structural capacities of the pavement and bridges.

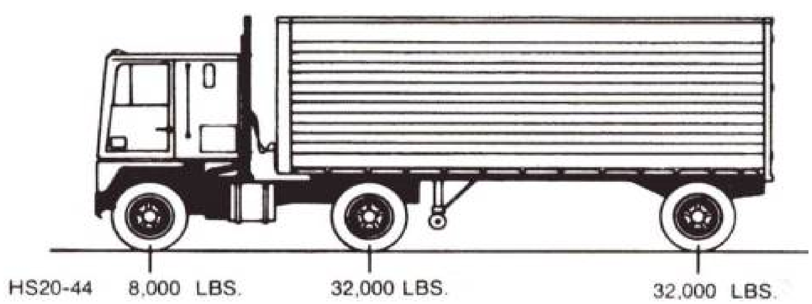


Figure 3-1 HS20 Truck from Federal Highway Administration, 2005

The following theories have been chosen to analyze the approach for analysis of highway bridges and pavement.

3.1.1 Punching Shear Approach

To examine the potential failure of the bridge structure, the bridge deck is a vital section to examine. The punching shear approach is used to examine the behavior of the bridge deck under heavy vehicle loads. Punching shear, or two-way shear action, is a popular failure mode used to analyze the strength of the structure. Punching shear is a failure type of reinforced concrete slabs or decks that are subjected to high localized forces. Brian Hewitt and Barrington de V Batchelor (1975) proposed an empirical approach to determine the punching shear capacity of a restrained bridge deck using the compressive membrane action. The punching shear is established by calculation of the punching load of the slab with known restraints. Restraining forces at slab boundaries are the results of compressive membrane action, fixed boundary action (action due to moment restraint) or cracking. These are all the results of punching shear failure.

Another punching shear model proposed compares the behavior of a bridge deck with a two-degree-of-freedom three-hinge-strut mechanism subjected to single transverse concentrated load at its apex in a bridge deck slab (Petrou 1996). Punching shear is considered to be related to instability. It examines brittle and ductile failure of the slab. The instability of the bridge has a direct effect on the impact of loading and thus contributes to brittleness of the failure mode in the deck.

According to S.D.B. Alexander and N.M. Hawkins (2005) in *Design Perspective on Punching Shear*, the shear resistance formula proposed includes an addition of the flexural resistance of the slab, while the American Concrete Institute (ACI) code does not take this parameter into account. The neglect of this parameter is described as a deficiency in the code's consideration for the column-slab assembly relationship.

The following calculation of punching shear is proposed:

$$V = 15\left(1 - \frac{0.75r}{d} - \frac{0.35V}{V_{flex}}\right) bd(f_c')^{\left(\frac{1}{2}\right)} \qquad \text{Equation 3-1}$$

Where V_{flex} is the product of the slab area tributary to the column and design load. The variables used and application of the formula are described in appendix D.

Among the approaches discussed above, the most rational approach for calculating the punching shear strength of a bridge deck is the ACI's 2008 Building Code Requirements for Structural Concrete and Commentary (ACI 318-08) code formula, which takes into account the dimensions of the load applied on the slab. All of the approaches use this method as the foundation and basis of their findings. Thus, using the Punching Shear approach outlined by the ACI is most efficient.

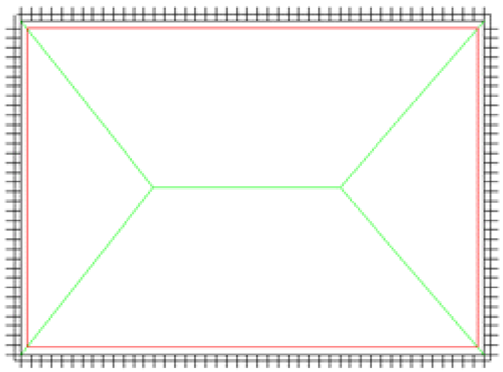
Additional information associated with punching shear assumptions are covered in Section 3.3 and the calculation and results are listed in Section 5.3.

3.1.2 Yield Line Approach

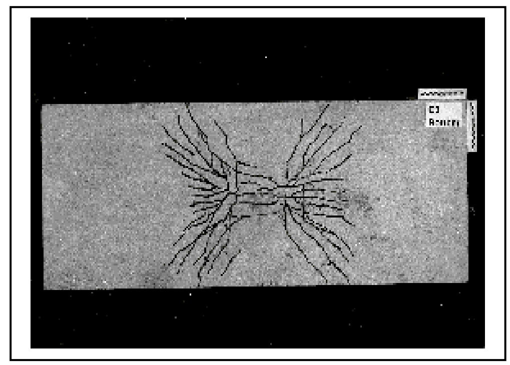
The yield line theory is used to examine the transversal behavior of the bridge deck under heavy vehicle loads. Yield line theory is used to predict ultimate loads on a concrete slab by postulating failure mechanisms based on set boundary conditions (as shown in Figure 3-2). Moreover, yield line analysis assists in predicting the location of the failure within a slab or in this case, the bridge deck. The yield line approach will be analyzed based on uniform reinforcement or an isotropic deck (decks of same materials properties). Some of the basic assumptions of the yield line theory are as follows:

- The structure is collapsing because of the moment or flexural collapse mode
- The slab has sufficient shear strength to withstand shear failure

- Concrete is assumed to be ductile at critical sections
- Small deformations compared with the overall dimensions are assumed



(a) Sketch



(b) Tested Failure Mechanism (Middleton, C.R. 1998)

Figure 3-2 Yield Line Pattern from Uniformly Loaded Simply Supported Slab

Park and Gamble (2000) suggest that there are two methods of analysis of the yield line theory. The first method of analysis is done by the fundamental principle of virtual work. Assuming a small arbitrary displacement, the sum of the work done by the forces will be zero. To apply the yield line theory, the yield line pattern is postulated and the bending moment is evaluated at segments of the slab that are in equilibrium under external loading (truck loads). Work will be done by heavy vehicle loads and internal actions along the yield lines.

Another method is analysis by equations of equilibrium. In the equilibrium method, the equations of equilibrium are calculated for each segment of the yield line pattern under bending and torsional moments, shear and external forces. The difference in these two methods are that in virtual work approach distribution and magnitudes of the shear do not need to be known in formulating the calculations along the yield line but in the equilibrium approach all actions need to be known in order to complete the calculation. In this case, yield line theory has been applied to concrete decks with external loads originated from truck axle loads.

However, Quintas (2003) suggests that the application of yield line theory is quite controversial. He describes that “normal method” or the equilibrium analysis and virtual work method at times do not present equal results or the “correct yield lines” simply because with the presence of shears and torsional bending, those forces may not act on the same yield line pattern as the bending moment. But when calculated along a pattern of yield lines that restricts the case in which only yield lines of the same sign meet at a point, it presents more representative results. Quintas concluded that yield line analysis can be approached more successfully using two basic ways: ‘‘normal moment method’’ and the ‘‘skew moment method,’’ where external forces (shear and torsional moments) are looked at as nodal forces acting at the same lengths along the yield line (Quintas, 2003). The method presented by Quintas will be used for application for bridge decks.

Additional information associated with yield line theory assumptions are covered in Section 3.4 and the calculation and results are listed in Section 5.4.

3.1.3 Girder Analysis of Bridge Girders

Truck weights also affect the condition of the bridge girders. When a truck moves across a bridge, it inflicts live loading. The loads result in the bridge experiencing bending, shear and fatigue stresses. In bridge design, engineers typically increase the static load by a fixed percentage (about 10 to 30 percent; 33 percent used in LRFD) to account for the dynamic load or moving load. The structure must be able to withstand other types of loading like self-weight, wind, thermal, earthquakes or dynamic loading. (FHWA, 2004)

For bridges, the bending moment is a point or equivalent point load times the distance of that load to the nearest support. There is a direct one-to-one relationship between bending moment and bending stress. Although bridge engineers consider and design for other stresses like shear and fatigue stresses (due to repetitive loading), in most cases, the bending moment/ stresses are the critical factors in the design.

The analysis in this report is focused on bending moment. In bridge design, the bending stresses caused by the live, dead or self-weight, and dynamic loads, will also accommodate the fatigue and shear stresses. If there is a high bending stress, the other stresses are also usually high and show a direct correlation between bending, shear and fatigue, although at different locations. Essentially, bending moment analysis assists in ensuring the strength and safety of the structure. Overall, the bending stress is a reasonable proxy for all stresses.

Additional information associated with girder analysis assumptions are covered in Section 3.5 and the calculations and results are listed in Section 5.5.

3.1.4 Potential Pavement Damage Approach

Various approaches are taken to estimate the potential pavement damage. The Equivalent Single Axle Load (ESAL) Design approach is used to measure pavement damage on Maryland local roads and highways to provide statistical support in examining the effects of lift-axle equipped vehicles. The ESALs approach was used to measure damage and to connect damage costs to axle load damage to the pavement on both rural roads and highways. This approach was chosen as the best approach after reviewing other references and an earlier report written by the SHA (1993) that investigated the effects of three-axle and four-axle Dump trucks entitled *The Impact of Dump Service Tag Vehicles on Maryland's Roads and Bridges*. The *AASHTO guide for design of pavement structures* (1993) outlines the design process for ESALs. The ESAL approach allows for the conversion of mixed vehicular traffic into its equivalent single-axle, 18,000 pound load. From this conversion, the relative damage per axle can be calculated.

In the ESAL approach, the load applied to the tire, pavement thickness, and spacing between tires are considered in the design approach and do not consider any traffic information (Y. Huang, 2004). Using the ESAL approach allows for isolation of the analysis of the lift axle. While many researchers use ESALs as the basis of their analysis, many use more sophisticated finite element approaches or road tests measuring strain, fatigue or rutting of the pavement to carefully examine the behavior of the pavement in relation to heavy loads applied to the surface. The AASHTO ESALs approach is very simple and compares very well to actual load tests using strain gauges and earth pressure measurements for damage (Lin et al, 1996). This approach uses a single standard axle of 18,000 pounds and compares with the actual vehicle axle loading. It also considers other factors such as structural design elements (for both rigid and flexible pavement), Average Daily Traffic (ADT), Average Daily Truck Traffic (ADTT), Lane Distributions as well as other appropriate information for repetitive traffic analysis. AASHTO provides separate ESAL values for flexible and rigid pavements due to tandem axles having a greater effect on rigid pavement (TRB 225, 1990). With the WIM Data provided by SHA, the ESALs approach can be used to investigate various truck axle loading configurations. The ESALs approach is a method used in determining not only the effects of each axle load but loading contributions on the overall serviceability of the pavement structure.

Figure 3-3 illustrates the pavement performance concept.

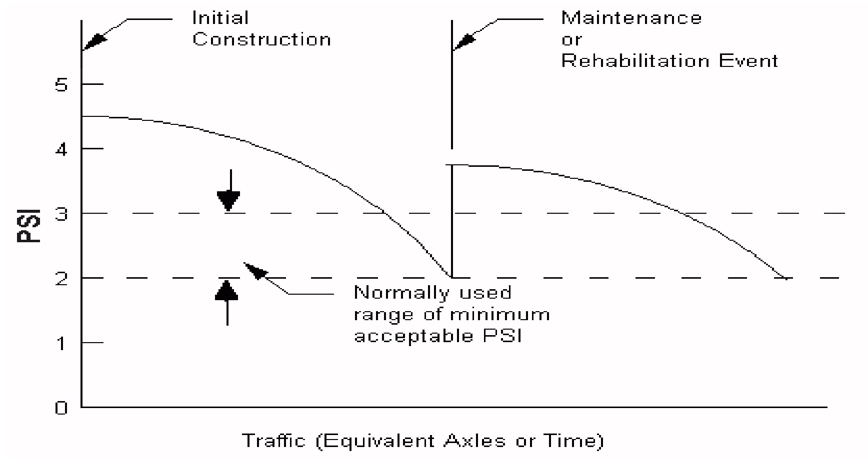


Figure 3-3 Concept of Pavement Performance Using Present Serviceability Index (PSI) (Hveem and Carmany, 1948)

In Figure 3-3, traffic in axles and time is graphed against the Pavement Serviceability Index (PSI). This shows that in the beginning of the pavement life cycle, the pavement is structurally sound and efficient. But more importantly, over time and as axle loads increase, the serviceability also heavily decreases as well.

Additional information associated with pavement damage assumptions are covered in Section 3.6 and the calculation and results are listed in Section 5.6.

3.2 Maryland Traffic Data Findings

Traffic data was collected using WIM data captured by a virtual weigh station from a state road as well as data collected by a team of state troopers. From this data collection, various statistical conclusions can be made. Data collections and their usages are described in the following sections.

3.2.1 Virtual Weight Station Data Collection

WIM data from MD 32 has been collected for this report analysis. This data was used to determine a nominal truck GVW and axle weights and spacing to use for theoretical computations. This truck would represent the ideal truck based on statistics. Because of the abundance of data, it has been broken down into months where one representative month of data from June 2010, Dump Truck (FHWA Class 7) vehicles have been filtered. After isolation of the Class 7 vehicles, proper statistical analysis is applied. A histogram of the truck gross weights is graphed with a normal fit of 5,299 Class 7 vehicles filtered from 309,450 vehicles (Figure 3-4).

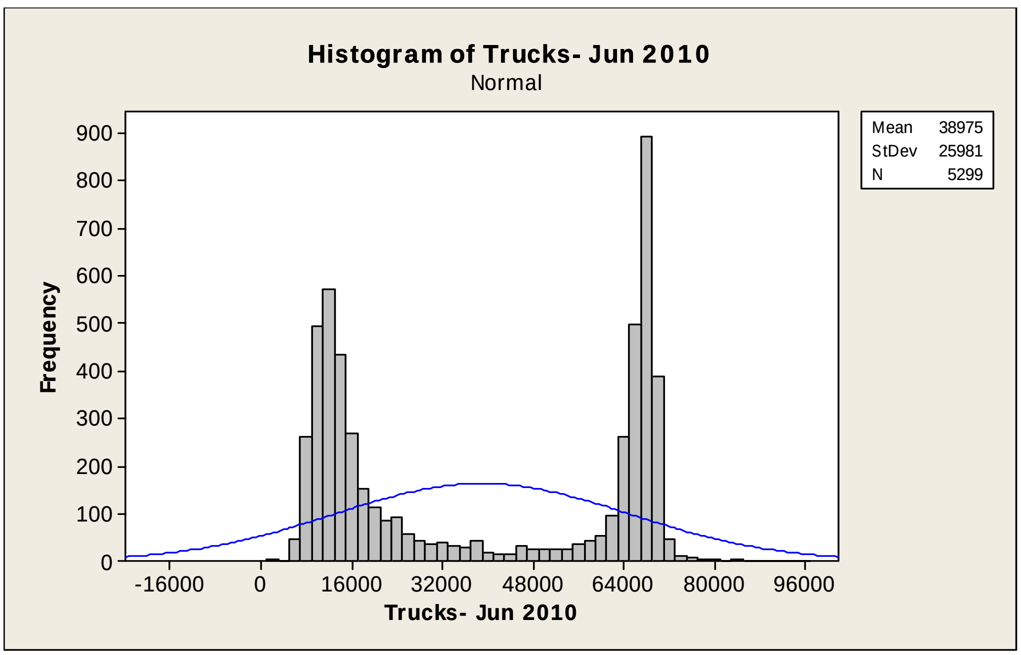


Figure 3-4 Distribution of Total Class 7 Vehicles for June 2010 from Virtual Weigh Station

As shown in Figure 3-4, it is found that there are two distributions present in the data. After reviewing the data, specifying new bounds of the data assists in narrowing in a particular vehicle population. Extremely small gross vehicle weight could be from possible WIM misreading. The new lower bound of the data was assumed to be 50,000 pounds (gross weight) up to the heaviest truck weighed. After choosing the new range, the total number of trucks greater than or equal to 50,000 lbs is 2,390 trucks. Repeating the above process the histogram yields the following in Figure 3-5.

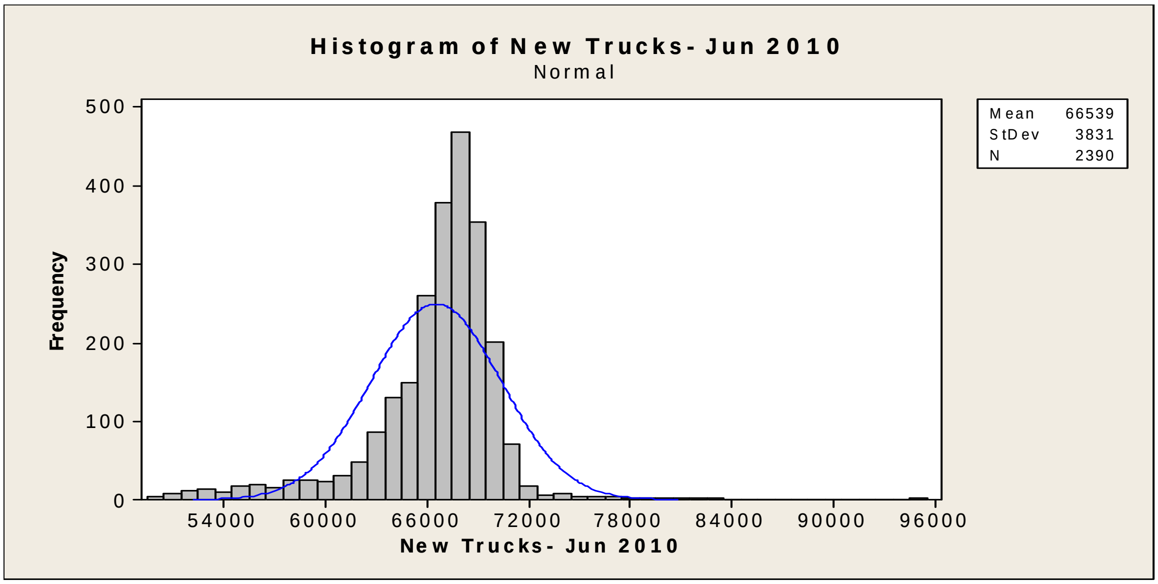


Figure 3-5 Distribution of Class 7 Vehicles with New Bounds

After reviewing this distribution, a new mean range is defined as 65,000-70,000 lbs which includes 1,645 trucks and is approximately 68.8% of the 2,390 trucks over 50,000 lbs (as shown in Figure 3-6).

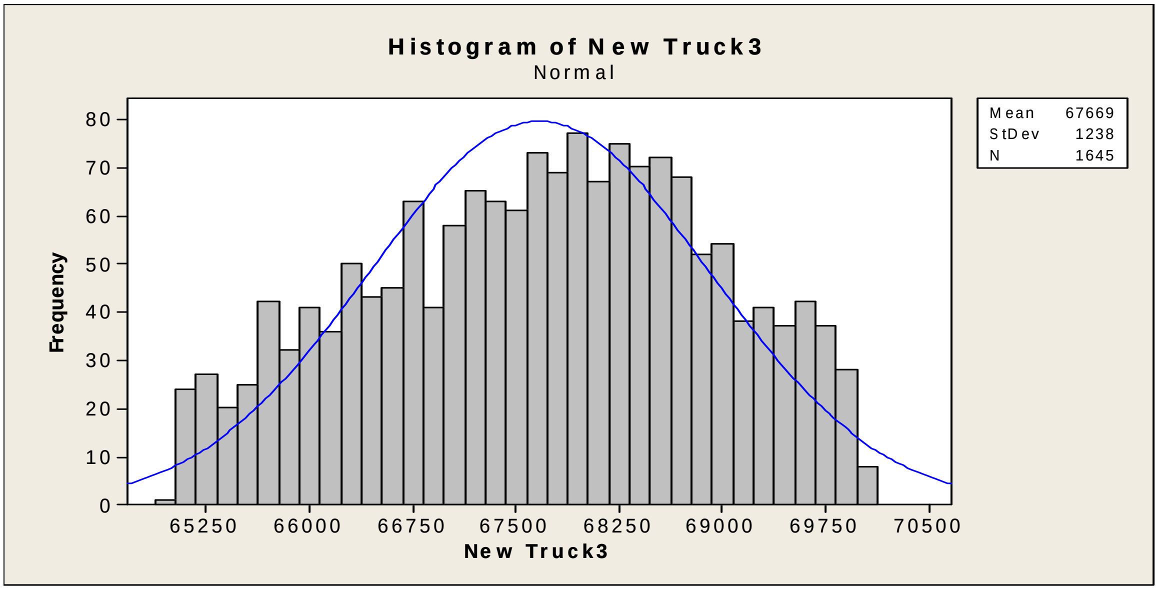


Figure 3-6 Distribution of Class 7 Vehicles with New Bounds 65,000 to 70,000 lb

The mean gross weight is 67,669 lbs with a standard deviation of 1,238 and the max gross weight is 70,000 lbs. Then the mean axle weights are found for each axle to complete statistical analysis. The nominal Truck configuration is as follows:

- Nominal Gross Truck Weight: 67,669.2 lb
  - Average Axle Weights:
    - Axle 1: 13,881 lb
    - Axle 2: 12,559.3 lb (Lift Axle)
    - Axle 3: 20,696.2 lb
    - Axle 4: 20,532.7 lb
  - Average Spacing:
    - Spacing 1: 12.48 ft
    - Spacing 2: 4.26 ft
    - Spacing 3: 4.39 ft

This data can now be used to apply all of the failure modes explained in the upcoming sections and will be demonstrated in Chapter 5:

Also, the lift axle can be isolated to look at its weight distribution. The following plot (Figure 3-7) shows the distribution of the lift axle.

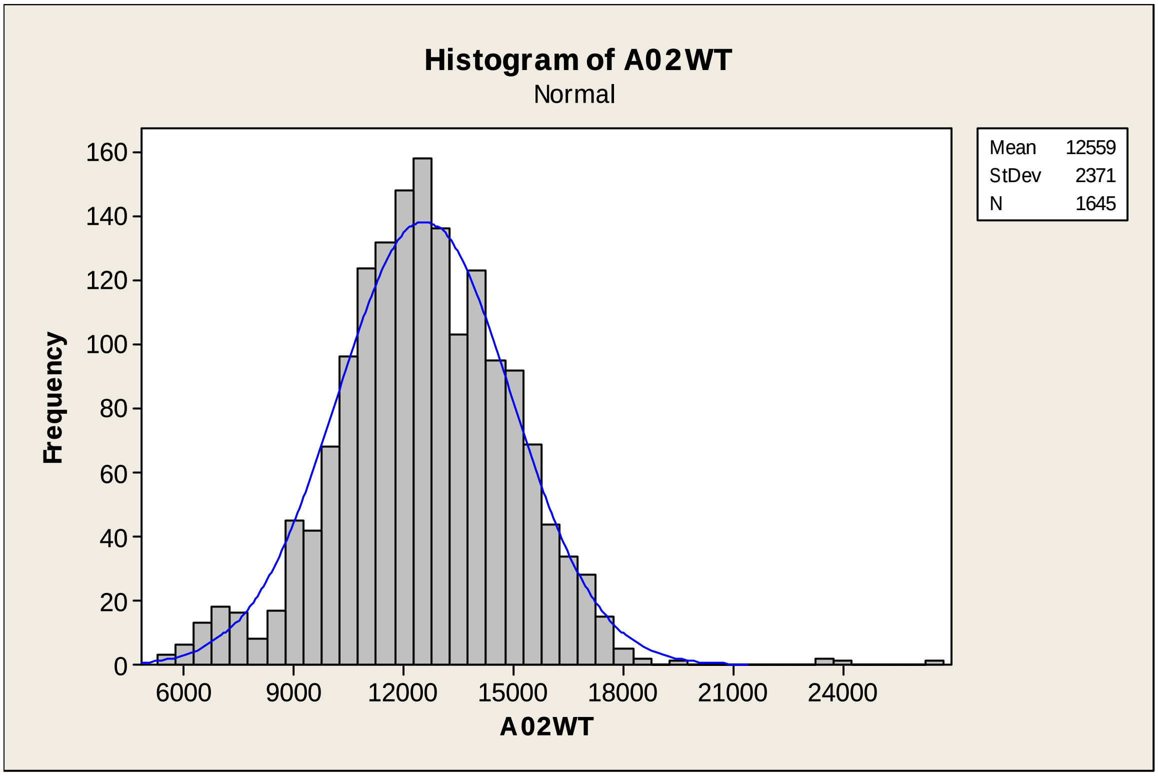


Figure 3-7 Distribution of Lift Axle Weights for the 65,000 to 70,000 lb Range

The mean lift axle weight is 12,559 pounds with a standard deviation of 2,371 pounds making the nominal lift axle weight at 14,930 pounds.

3.2.2 Safety Initiative Data Collection

The safety initiative was put together to collect sufficient raw data for trucks traveling on Maryland highways. Teams of roving crews were sent out to target trucks with lift axles including four-axle dump trucks as well as other configurations. Roving crews were to capture trucks based on the following criteria:

- Overweight Vehicles
- Trucks having at least one lift axle or
- Equipment violations

For this initiative, inspection information and data from 12 roving teams was collected from February 15 to March 20, 2011. The targeted trucks were checked to ensure that they were in compliance with weight regulations as well as other equipment and operational compliance based on Maryland vehicle law. This initiative was completed statewide near all of the static weigh stations (as shown in Figure 3-8). The survey criteria in full length as well as the results can be found in Appendix B.

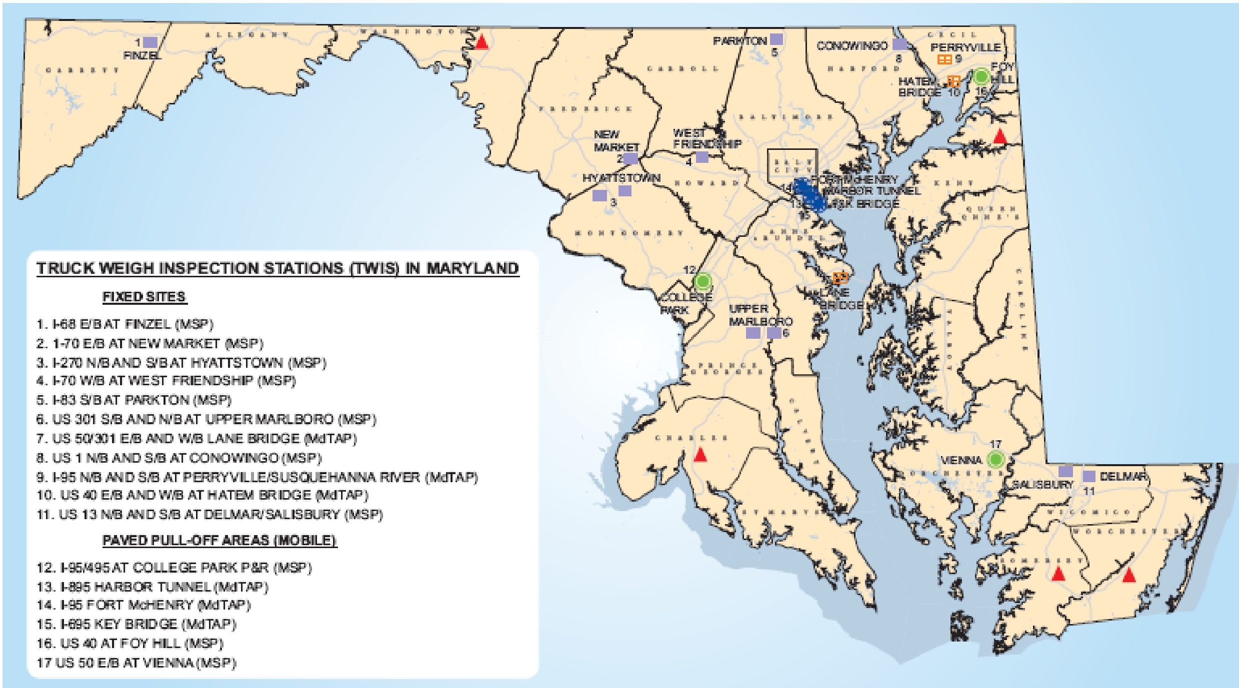


Figure 3-8 Maryland Truck and Weigh and Inspection Station Facilities

3.3 Punching Shear Assumptions

Based on the study of different approaches for punching shear, the approach proposed by the American Concrete Institute (ACI) code was selected. The ACI code approach takes into consideration the perimeter of the punching shear region and the area of influence which depends on the configuration of the load accounted by the factor β.

The following formula is proposed for the calculations (Mitchell, 2005):

$$V_c = \left(1 + \frac{2}{\beta}\right) * (f_c')^{\frac{1}{2}} * b_0 * \frac{d_{av}}{6} \qquad \text{Equation 3-2}$$

Where,

V_c is the punching shear resistance of the block.

d_{av} is the average effective depth.

b_0 is the perimeter of the critical section located at a effective depth 0.5dav.

β is the ratio of the long side to the short side of the concentrated load or the load reaction area.

The ACI code places an upper limit on $(f_c')^{1/2}$ of 100,000 pounds. However in the design, we assume f_c'=4000 psi.

Some of the following assumptions were made in calculating the punching shear:

- As per the standard, the contact area of the tire was assumed to be 10 inches by 20 inches ($l*b$). The calculations of the length and width of the loaded area were made on the basis of this assumption.
- In this method, the punching shear was assumed to act uniformly over the loaded area and the punching shear is maximum at a distance 0.5 d_{av} from the edges of the load combined together in the form of a rectangle.
- The average distance and loads are calculated on the basis of statistical data for the nominal configuration of the truck from section 3.2.

3.4 Yield Line Theory Assumptions

Quintas (2003) proposed two methods of determining yield line patterns by combining two different ways of performing yield line analysis. This combination facilitates a more comprehensive approach of analysis for deck slabs. These are ‘‘normal moment method’’ and a new ‘‘skew moment method.’’ In normal moment method, only bending moments are supposed to act at yield lines. However, in the skew moment method, twisting moments, in addition to bending moments, act along yield lines. The normal moment method assumes that bending moments can only act along yield lines.

The calculation of bending and twisting moments acting in any direction becomes simple if bending moments are represented as vectors normal to those lines and twisting moments as vectors with the same direction of lines along which they act. Bending and twisting moments are modeled as vectors with the same direction of the stresses produced by these moments. The two bending moments acting at a point on a slab are designated as M_a and M_b. Meanwhile, twisting moments are designated as M_{ab} and M_{ba} or simply as M_{ab} since M_{ab}=M_{ba}. The two principal bending moments are designated as M_a and M_b and the shear force acting at a yield line as T_a=0 for simply supported slab. Yield Lines should be modeled respectively as the following:

- Positive yield line is represented as one crooked line
- Negative yield line is two crooked lines
- A free edge is a straight line
- A simply supported edge is two straight lines
- A clamped edge is a family of parallel lines,
- And a column is a circle.

It is assumed that the slab yields at any point and in any direction with a positive yield bending moment. If it is a simply supported span, T_a=0, and both yield line methods normal can be interchangeably used yielding the same results. (See Figure 3-9 for Simple Supported Slab example with notations)

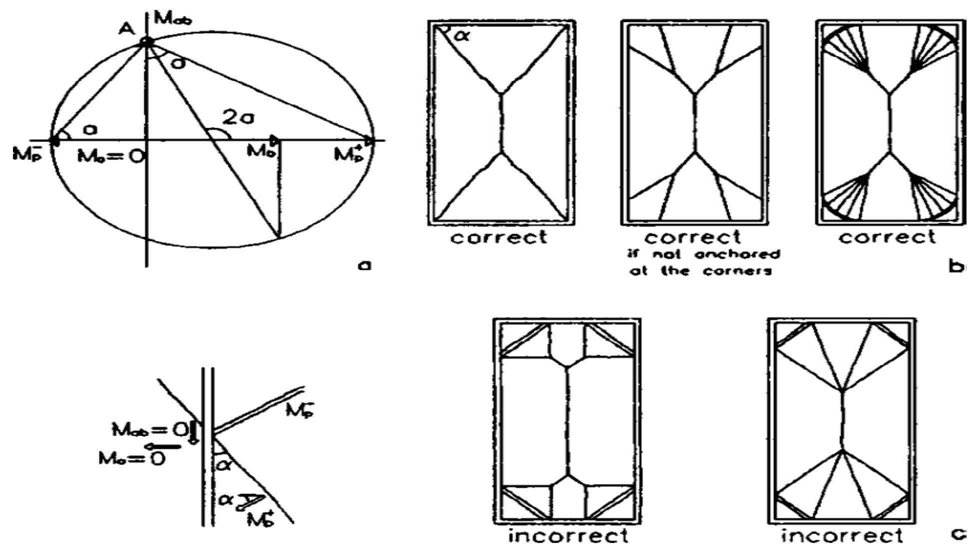


Figure 3-9 Examples of Yield lines Notation (Quintas, 2003)

The tandem and tridem loading configurations (nominal trucks from section 4) are applied from the statistical data obtained from calculations. The average distance between the steering axle and the lift axle (2^{nd} axle) is 12.48 feet. However, this distance is large compared to the distance of a typical slab in yield line analysis. Thus, only the 2^{nd}, 3^{rd}, and 4^{th} axles are taken into consideration and the load is the sum of these individual forces.

The failure pattern is assumed to be a straight line based on calculations. The moment comparison is made on the basis of the angle of the failure pattern. The failure plane is assumed to make an angle of 45 degrees with the transverse axis of the slab and the moments are calculated. The moments are described in the figure below (Figure 3-10). The longitudinal length l_y is a function of the girder spacing and the angle of failure

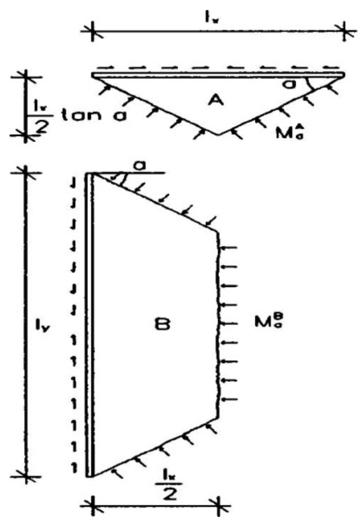


Figure 3-10 Moment Regions of a simply supported slab (Quintas, 2003)

The following formulas were used to calculate the bending moments (or failure point) created by heavy truck loads and in turn determine yield line theory.

$$M_x^A = \frac{p{l_x}^2}{24}\tan(\mathrm{a})^2 \qquad \text{Equation 3-3}$$

$$M_x^B = \frac{pl_x^2}{8} - \frac{pl_x^2}{12}(\tan \mathrm{a} \,/\, \lambda \;) \;\; \text{where } \lambda = (l_x/l_y) \qquad \text{Equation 3-4}$$

l_x is the girder spacing

l_y is the distance between stiffeners

a is the angle between yield line and principal direction, and

p is the load per unit square feet on the slab.

3.5 Girder Analysis Assumptions

There are various loading that effects the behavior of the bridge structure. Bending Moment is the most popular index in the analysis of bridge girders. In the simplified girder analysis, the live load bending moment is calculated based on the truck loading and spacing configurations. Then, by using the influence line fundamentals with distribution and impact factors, maximum live load bending moment is calculated.

An influence line uses bending moment at a particular section of the girder, as a unit load moves over the span of the bridge structure. For purposes of this research, the moving unit load is the nominal truck with the respective configuration. The influence line represents the value of that function when the unit load is at that particular point on the structure. Influence lines provided a systematic procedure for determining how the axle loads in a given part of a structure vary as the applied load moves about on the structure. The influence line approach for moments shows the variation of response at one particular section in the structure caused by the movement of a unit load from one end of the structure to the other. By the usage of influence line method, the maximum live load moment (based on LRFD approach) was found at mid-span of the bridge structure given various spans.

For the live load moment calculation, both tandem (lift axle raised) and tridem (lift axle down) axle truck configurations are calculated. The center of gravity is calculated for both truck configurations and then setting the center of gravity at the mid-span of the structure to calculate the effect of the bending moments at the midpoint for the maximum moment. The moment distribution factor for the live load is calculated based on span length as:

$$D_m = 0.075 + \left(\frac{S}{9.5}\right)^{0.6} \left(\frac{S}{L}\right)^{0.2} \qquad \text{Equation 3-5}$$

Where S is the girder spacing and L is span length

For design moments and shear, the impact factor is assumed to be 0.33 from the LRFD standards. The two factors are added to yield the maximum moment at the mid-span for both axle and spacing configurations. Due to the isolation of the truck loads, the design lane load (uniformly distributed load) is not used in this calculation.

3.6 Pavement Damage Assumptions

The effects of lift-axle equipped dump trucks on pavement performance depend on many different factors. Some of the factors are:

- Traffic volumes;
- The structural design of the pavement;
- Pavement construction, materials and maintenance; and
- Truck gross weights.

More specifically, in this report, multiple-axle heavy loaded vehicles are investigated. The AASHTO ESAL approach calculates the relative damage to a pavement structure due to different axle loading. It defines the damage per pass to a section of pavement as it relates to the damage per pass of a standard axle load which has an 18,000 pound single axle load. The approach looks at the total number of passes of the standard axle load during a given period and is computed as follows:

$$\log\left(\frac{W_{t18}}{W_{tx}}\right) = 4.79\log(18+1) - 4.79\log(L_x + L_2) + 4.33\log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \qquad \text{Equation 3-6}$$

Where,

W: axle applications at the end of a given period of time where W_{18} is number of 18,000 lb (80 kN) single axle loads.

L_x: axle load being evaluated (kips)

L_{18}: standard 18,000 pound axle load

L_2: code for axle configuration (provided by the AASHTO Manual i.e. 1 for single axle 2 for tandem etc.)

$$G_t = \log\left(\frac{4.2-p_t}{4.2-1.5}\right) \text{ where } p_t \text{ is the ratio of lost in serviceability} \qquad \text{Equation 3-7}$$

$\beta = 0.4 + (\frac{0.081(L_x + L_2)^{3.23}}{(SN+1)^{5.19} L_2^{3.23}})$ Equation 3-8

where SN is the structural number of the pavement and varies based on structural design specifications of each road.

For Rigid Pavement:

$\log\left(\frac{W_{t18}}{W_{tx}}\right) = 4.62\log(18+1) - 4.62\log(L_x + L_2) + 3.28\log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}}$ Equation 3-9

$G_t = \log\left(\frac{4.5-p_t}{4.5-1.5}\right)$ where p_t is the ratio of lost in serviceability Equation 3-10

$\beta = 1.0 + \left(\frac{3.63(L_x + L_2)^{5.20}}{(D+1)^{8.46} L_2^{3.52}}\right)$ where D is the thickness of the slab Equation 3-11

This yields the Equivalent Axle Load Factor (EALF). The EALF will be used later to calculate the ESAL. It is assumed that the fourth power rule can be used in verification of the calculation of the EALF. Since it was found that W_{tx} is a single axle, it is reasonable to assume that the tensile strains of the pavement are directly proportional to the axle loads (Huang, 2004). The fourth power calculation is as follows:

- $EALF = (\frac{L_x}{18})^4$ where L_x is the load on a single axle, Equation 3-12
- $EALF = (\frac{L_x}{L_s})^4$ Equation 3-13

Where L_s is the load in thousands of pounds on the standard axles, which have the same number of axles as L_s

Other factors also contribute to the determination of the ESAL that are more connected with traffic analysis. To compute the ESAL, the following equation is used:

$ESAL = (ADT)(T)(T_f)(G)(D)(L)(365)(Y)$ Equation 3-14

ADT is the Average Daily Traffic on the specified roadway. The ADTT is the Average Daily Truck Traffic (T) is the Average Daily Truck Traffic which is a percentage of the ADT. The Truck factor (T_f) takes the sum of ESALs for all trucks weighed and divides it by the number of trucks weighed. The Growth factor (G) is a way to project the growth of truck traffic over a design period or at a yearly rate. The Distribution factor (D) serves as a way to distribute traffic by number of lanes (L) to make a more accurate prediction for pavement and Y is the design period in years. From the calculations, the impact of dump trucks can be determined and compared based on whether the lift axle is deployed.

In this report, the ESALs approach is used to compute the effects of Dump Service Vehicles (four-axle dump trucks with lift axle) by isolation of dump truck data. While the final ESALs equation considers factors like ADT and ADTT, these are not used in the ESALs analysis because the ESALs calculations in this report are not based on mixed traffic. Thus, the analysis stops after the calculation of the Equivalent Axle Load Factor (EALF), which is substituted as the final ESAL calculation. After examining the nominal truck case based on statistical data, conclusions are made and listed in Section 6.0 as to what cases cause more damage in the given parameters and conditions.

The performance life of the pavement can also be modeled. Aside from repetitive loading and traffic, environmental effects also can affect the life span of pavement. In order to show the deterioration of pavement over time, the below model was used:

$$\delta = -\frac{\ln\left(\frac{P_T}{P_I}\right)}{L} \qquad \text{Equation 3-15}$$

Where δ= decay rate due to the environment

P_T= Terminal Present Serviceability Rating (PSR)

P_I= Initial Present Serviceability Index

L= Maximum Life time of a pavement section

These terms are used to compute the PSR due to the Environment:

$$P_E = P_I e^{(-t\delta)} \qquad \text{Equation 3-16}$$

where *t*= is the number of years.

Theoretical evaluation and analysis using the approaches listed in Sections 3.1, nominal trucks based on VWS data listed in Section 3.2 and assumptions for all approaches listed in Sections 3.3 through 3.6 are covered in Chapter 5 of this report.

Chapter 4: Policy Research

4.1 Maryland Truck Size and Weight Regulations

In the State of Maryland, commercial vehicle laws were created from the framework of the Federal Highway Administration (FHWA) and the Code of Federal Regulations. The Federal Bridge Formula Law was created under the Federal Aid Highway Amendments of 1974 to limit axle weights and gross weights and is used on Maryland interstates and states routes. Some states were allowed to utilize their grandfather rights to maintain truck weight and size requirements post implementation of the Federal Bridge Formula Law. In 1991, The United States Congress made provisions to the Intermodal Surface Transportation Efficiency Act (ISTEA) that specifically allowed Maryland to operate 70,000 pound four-axle dump service vehicles in Alleghany and Garrett Counties. In 1993, the Maryland General Assembly enacted a law allowing statewide operation of these dump service vehicles (SHA, 1993), making them the only exception to Federal Regulations on roads and bridges in Maryland.

The new provision introduced a new approach to Maryland roads and dump trucks. Maryland began to not only discuss dump truck gross vehicle weights but the number of axles and loading also became very important factors in the preservation of Maryland highways and bridges.

4.1.1 Dump Service Registered Vehicles (DSVs)

Dump service registered trucks are one of the more prominent truck types that receive attention in Maryland due to their potential damage to the state's highway system. In 1993, the Maryland Department of Transportation established the Dump Truck Technical Task Force to develop various configurations, design and loading criteria for dump trucks as well as lift axles. The "Class E" Dump truck is typically for hauling loose materials due to its mechanical means of self-unloading. The gross weight limitations (TR 13-919) for a dump service truck are briefly summarized as follows:

- 40,000 pounds for two-axle truck
- 55,000 pounds for three-axle truck (registered after June1, 1994)
- 65,000 pounds for gradually phased-out three-axle truck (for vehicles registered prior to June 1, 1994)
- 70,000 pounds for four or more axles

In the effort to make the transition to a four-axle dump truck loaded at 70,000 pounds from a three-axle truck at 65,000 pounds, the Maryland State General Assembly allowed dump trucks already registered as DSVs to continue to operate at 65,000 pounds during the phase out period. Legislation set a 20 year operating window for the phase out process of three-axle trucks until May 31, 2014 (Maryland Transportation Article, 13-919).

Except on a divided highway with two or more lanes in each direction or while it is unloaded, DSVs must not operate at more than a speed of 45 miles per hour. There are also a few exceptions for Alleghany and Garrett Counties where (1) standard GVW for dump service vehicles with four or more axles is 70,000 pounds, and (2) DSVs are not subject to any other restrictions of the Maryland Vehicle Law on the weight, gross weight, or axle loads unless the

GVW "exceeds its maximum registered gross weight by 10 percent or one of its axles is not carrying at least 15 percent of the vehicle's total gross weight" (TR 13-919).

Eastern shore counties of Maryland and bordering state, Delaware, also have a reciprocity agreement for DSV trucks. The agreement was put into place in January 1996 to accommodate for the DSV traffic in both states. For Maryland, this agreement is limited to the Eastern Shore.

4.2 National Survey Results

4.2.1 Lift Axle Survey

A 25-question survey was sent by the University of Maryland Bridge Engineering Software and Technology (BEST) Center to all 50 states' Department of Transportation and some Canadian Provinces. The survey addressed various topics that pertain to Lift Axle Trucks and Regulations. The survey examined the following topics:

- Section I, Vehicle Weight Policies: 9 questions
- Section II, State Truck Regulations: 2 questions
- Section III, Deterioration by Trucks, : 2 questions
- Section IV, Lift Axle Regulations: 12 questions

28 survey responses, including Maryland, were received out of 50 state DOTs, as well as one (1) survey from British Columbia (Canada). There were also two (2) non survey responses from New Jersey and Saskatchewan (Canada) where they provided short statements as their response. Figure 4.1 shows the states that responded to the survey.

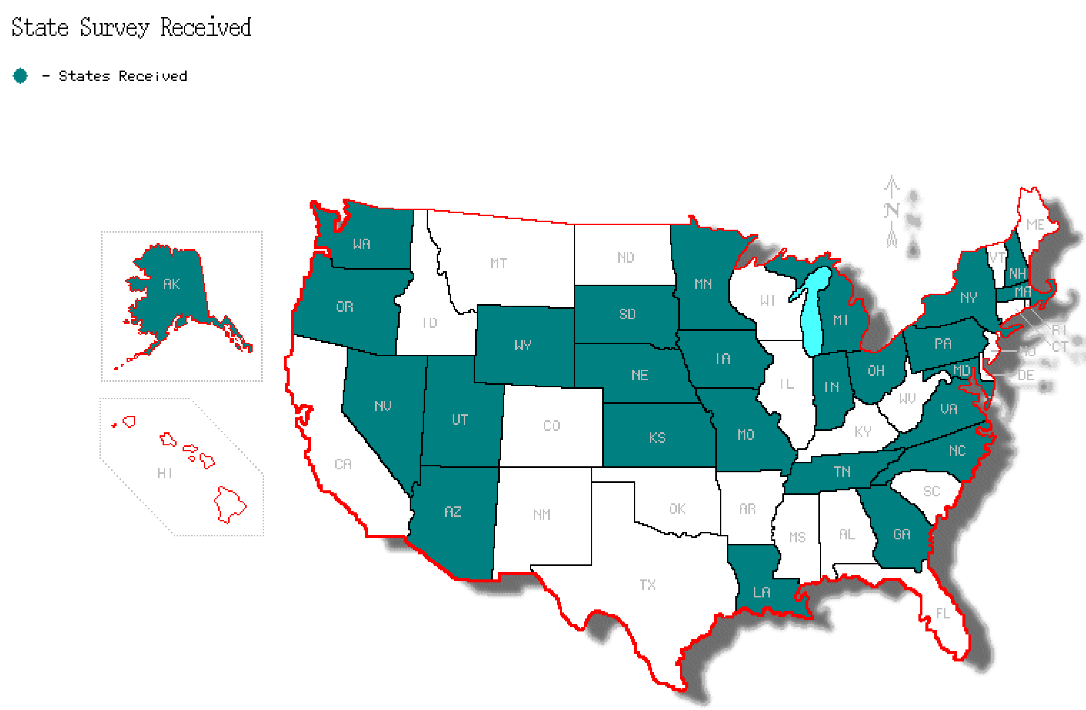


Figure 4-1 Map of State Survey Responses

The survey did not yield responses from the larger import/export states, such as Texas, California, and Florida. Had those states responded the results may have been different considering those states have major import/export businesses. The State of New Jersey commented that there was not enough information to answer the survey thoroughly while the Saskatchewan Province discussed their lift axle policies and compared them to some of the other Canadian Provinces.

4.2.1.1 Survey Section 1: Vehicle Weight Policies

The survey discussed vehicle weight laws as they pertain to FHWA regulations. It discussed the aspect of "grandfathered rights" where states were able to sustain their existing laws after the creation and enactment of new laws. This becomes especially important in weight laws because states use their grandfather rights to maintain Gross Vehicle Weights that are above the 80,000 pound maximum limit. Figure 4-2 shows the states responses for "grandfathered rights."

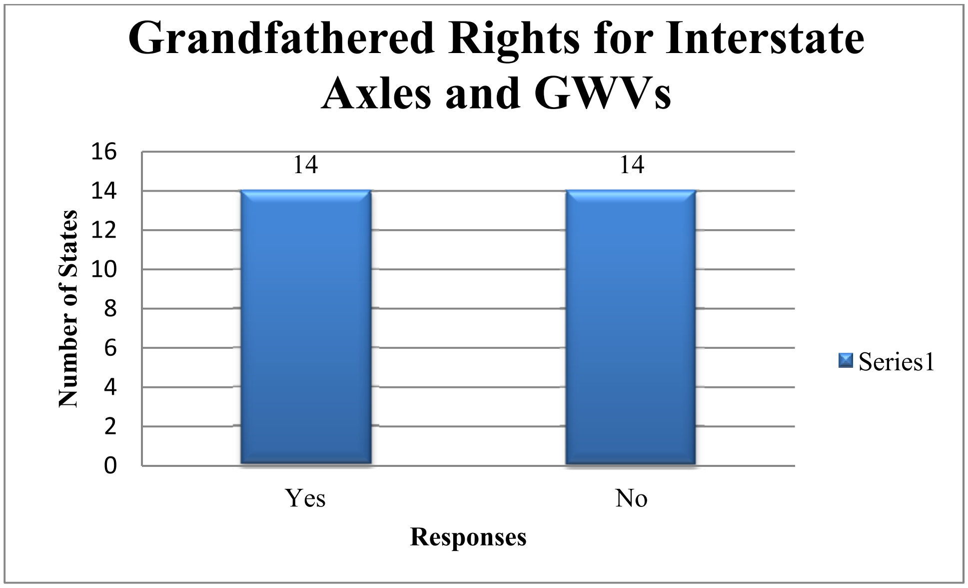


Figure 4-2 Graph of Survey Response for Question 1

Q1: Does your state currently utilize its grandfathered rights for Interstate axle and gross weight limits?

The states responses were equal for the topic of grandfathered weight rights. Half of the states surveyed follow the mandated Federal Gross Weights and Axle Weights on their interstates, where the other 14 states have used grandfathered rights to carry above 80,000 pounds on their interstates. Maryland is one of the states that have grandfathered weight rights, but they only pertain to DSVs on interstates, local and state routes.

As stated earlier in this chapter, Maryland dump service vehicles are the exception to the Federal Bridge Formula Law (FBF-B). Maryland law stipulates that "any vehicle with a gross maximum weight in excess of 73,000 pounds may travel only on State highways, except while making a delivery or pickup and then only when traveling by the shortest available legal route to or from the State highway for the purposes of making such delivery or pickup." (TR 24-108) From this, there are times that Maryland dump service vehicles are operating on roads where usually not permitted, but allowed solely for business purposes of deliveries. The legal route given for a particular delivery may be a route where without this exception the dump service vehicle would otherwise be in violation of gross weight laws. Figure 4-3 and Figure 4-3 show the states' compliance with the FBF-B Law on both interstates and state highways.

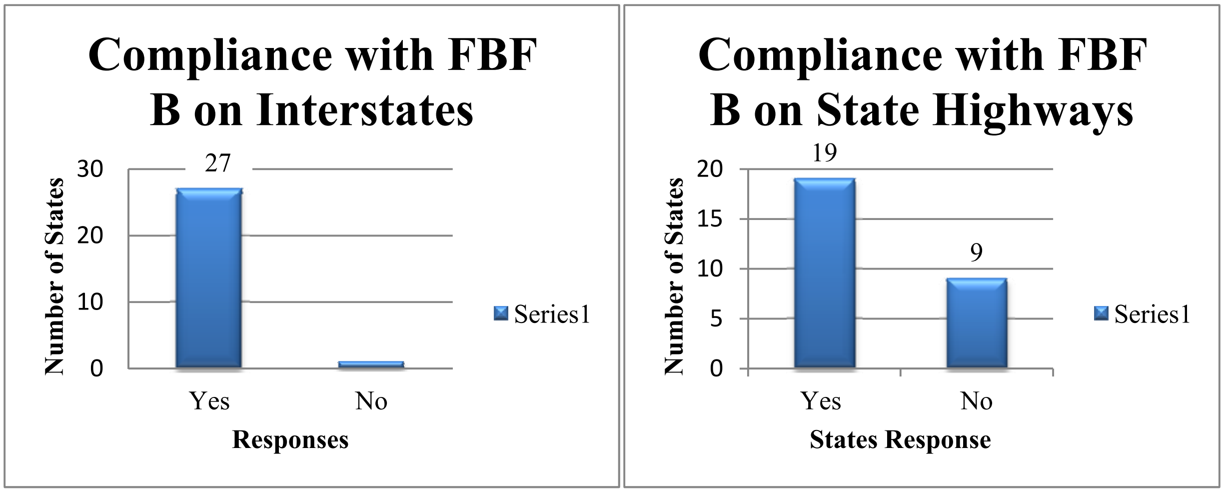


Figure 4-3 (L) on Interstates & Figure 4-4 (R) on Local and State Routes: Survey Responses for State Compliance with FBF-B Law

In the figures above, more states work to comply with Federal Regulations on the Interstates and seem more lenient on State and Local Routes. With 27 states complying with FBF-B on Interstates, Maryland included a "YES" response but the exception to the compliance is through the Dump Service Vehicle Law. On local and state routes, only 19 of the 28 states comply with Federal Bridge Formula Law on their state and local roads.

Aside from FBF-B Law, overweight trucks also become a concern on roadways and potentially contribute to roadway deterioration and bridge fatigue and cracking. As a result, states were asked to describe how many overweight trucks travelled on their roads.

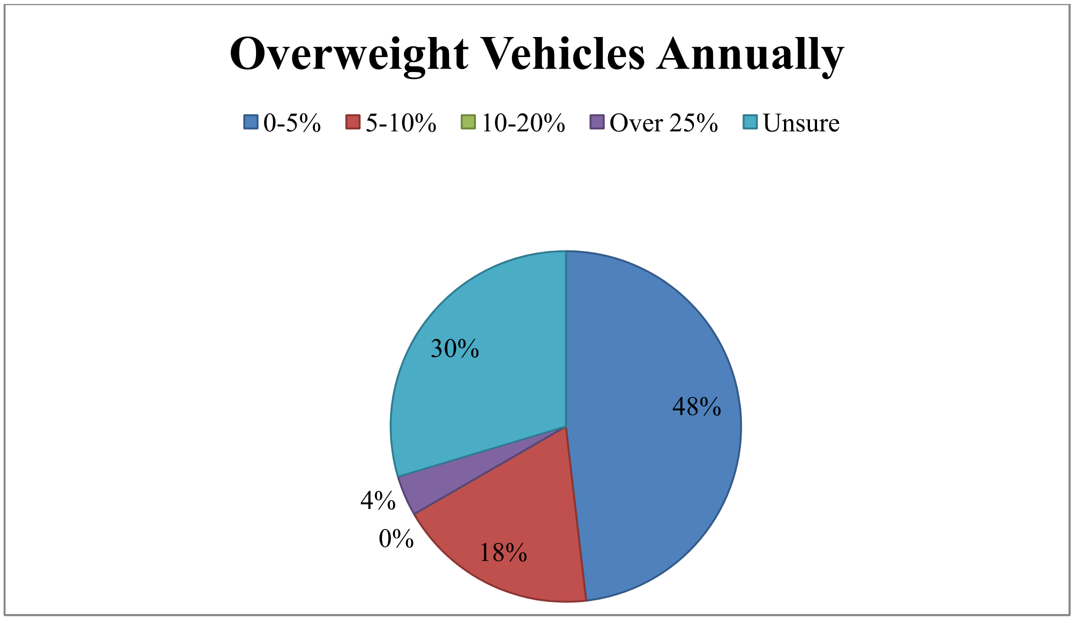


Figure 4-5 Survey Responses for Annual Percent (%) of Overweight Vehicles
Q7: What range best describes the number of overweight trucks annually statewide?

Figure 4-5 shows that almost half (48%) of states described themselves as having 0-5% overweight trucks on their roads annually, Maryland included. While 30% of states were unsure and did not have the information to be able to provide an answer, 18% of states chose 5-10% as the range that best describes the amount of overweight trucks, while 4% of states expressed over 25% of their trucks were overweight annually.

The survey also discussed weigh station records and computer software used for record keeping and enforcement. Eleven states review their weigh station records on a monthly basis while six states review their weigh station data weekly. Twenty-four states are able to weigh multiple axles/lift axles. Thirteen states reported use of a special computer program for weigh station data, but only a few states provided the names of the programs. Some programs used are Tradas, MSC Enforcement, Microsoft Excel and in-house programs. All states surveyed have enforcement personnel assigned to conduct roving operations. Twenty states surveyed were unaware of instances where enforcement was unable to sufficiently weigh a truck with multiple lift axles due to insufficient number of scales.

4.2.1.2 Survey Section II/III: State Truck Regulations and Deterioration by Trucks

This survey section asked states to compare their state truck regulations to the Federal Truck Regulations, especially as they pertain to weight limits. Twenty- two states surveyed have their own state truck regulations. Nine of those states have gross vehicle weights that exceed the Federal GVW standards of 80,000 pounds and range up to 129,000 pounds. Only six have state axle suspension requirements including Maryland, where specifications simply require that suspensions are in safe operating condition.

While deterioration could be an issue due to several factors discussed earlier, states were also asked about potential damage to their roads and bridge structures by trucks. Twenty-two states were unsure about how much trucks in general contribute to pavement and roadway damage. Twenty states were unaware how much overweight trucks contribute to damage to bridge structures. This illustrates that most states either do not have a way of measuring how much damage trucks do to roads and bridges or they simply have not implemented a means to measure this.

4.2.1.3 Maryland Lift Axle Regulation

The State of Maryland has seen an increase in the use of lift-axle equipped trucks, in particular, DSVs. Maryland currently only has regulations for four-axle-or-more DSVs equipped with lift axles. In order to meet Maryland requirements, the lift axle must "ensure sufficient air pressure which will maintain a minimum axle load capacity of 13,500 pounds, with a maximum tolerance of minus 1,500 pounds, when fully engaged on an evenly loaded vehicle with a GVW of 70,000 pounds" (COMAR11.15.27.03). If the vehicle GVW is between 55,000 and 70,000 pounds, the minimum lift axle loading is 10,000 pounds for GVW of 65,000-69,999 pounds and 8,000 pounds for GVW of 55,000 to 64,999 pounds. (COMAR 11.15.27.07) Aside from weight restraints, there are other operational requirements for the proper usage of the lift axle:

- The lift axle shall be designed so that when in the down position the axle can only be fully engaged.
- A switch capable of only fully engaging or disengaging the lift axle may be located in the cab of the vehicle and an air pressure adjustment control may not be located in the cab of the vehicle.
- A standard automotive air pressure valve for the lift axle shall:
  - Be supplied on each vehicle that uses a lift axle;
  - Have an external valve stem;
  - Be located on the outside of the passenger side of the vehicle towards the rear of the cab; and
  - Be readily accessible and visible for examination (COMAR11.15.27.05).

The lift axle may be disengaged when turning at an intersection or sharp curves (15 mph). The lift axle may also be raised when entering and exiting the delivery locations. The lift axle may be raised when unloading cargo and can be disengaged for ¼ mile before and after authorized raising during operation (COMAR 11.15.27.07).

As observed earlier in this section, Maryland does not make mention of the role of lift axles in the axle configuration for any of the above DSV configurations. The regulations are for trucks with four or more axles and most Maryland DSVs are four-axle dump trucks with one of the axles being a lift axle. The DSV regulation also explains enforcement and fines for non-compliance.

Twelve of those states responding to the survey have lift axle regulations and in Georgia lift axle trucks are banned. The figure below shows the Survey Responses for Lift Axle Regulations.

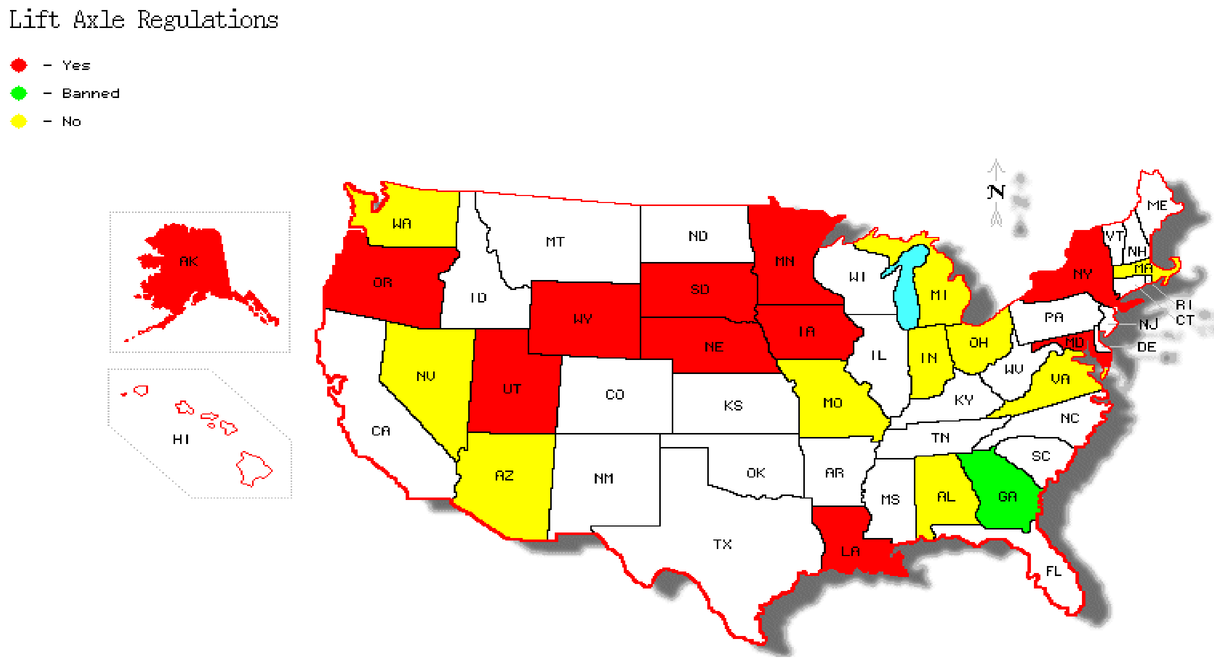


Figure 4-6 Lift Axle Regulation Survey Responses Question 14

Q14: Does your state have specific lift axle regulations?

The survey also asked states to examine specifications of their lift axle configuration. Often times lift axles are deployed when they should be raised and this could be from driver neglect to raise the axle or malfunctioning of automatic control system. Figure 4.7 below shows that of the states surveyed about 1/3 have specifications that fall into the categories shown.

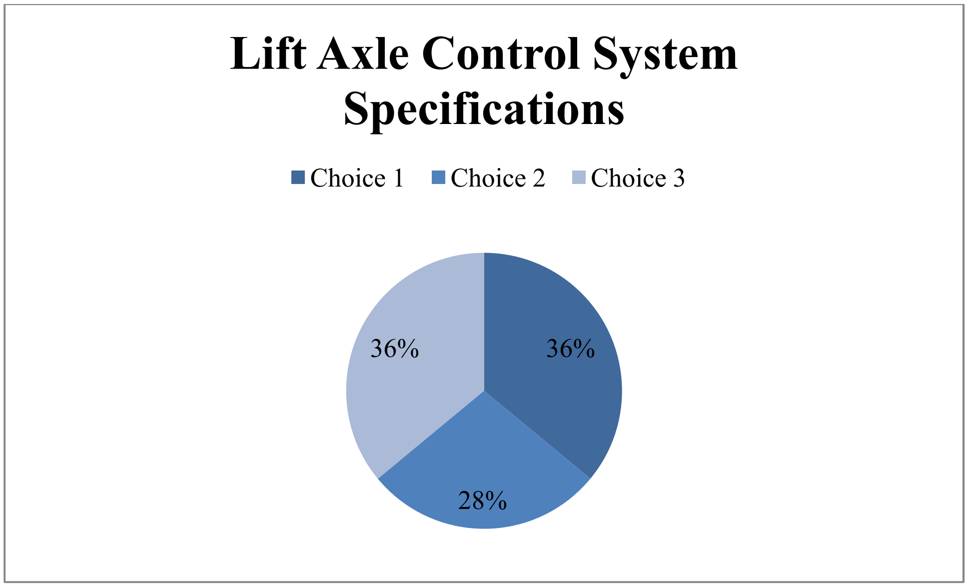


Figure 4-7 Survey Responses for Lift Axle Control System Specifications

Choice 1: The lift axle control system is on the interior of the truck and controlled by the driver,

Choice 2: The lift axle control system is on the exterior of the truck and controlled by the driver after load has be added or removed to/from the truck.

Choice 3: There are no current specifications for control of lift axles.

Aside from lift axle control systems and policies, the survey also asked states about suspension requirements, lift axle configurations, and equipment. Eight states use Federal standards for lift axles (recognizing the lift axle as a fixed axle) while 11 states allow lift axle trucks to operate on state roads based on specific lift axle configurations. Eight states also have lift axle steering or equipment specifications. In Maryland, the equipment specifications need to be in safe operating condition as well as meet the criteria outlined in COMAR 11.15.27.05 Moreover, only five states specified that there are lift axle configuration specifications. Of the five states that have lift axle configuration specifications, only four of the states identified this in the 11 states above. In addition, the survey also asked states to describe the amount of overweight trucks with lift axles weighed annually. Seventeen states were unsure of the amount while 17 others claimed dump trucks were the most popular for lift-axle equipped truck types.

4.3 Canadian Survey Results

As mentioned in Chapter 2:, Canada has substantial experience in lift axle technology and there are distinct differences among the regulations in each province. British Columbia responded to the survey answering based on their policies. The maximum gross vehicle weight combination is 140,000 pounds compared to the United States' 80,000 pounds. The respondent stated that lift axles are banned in British Columbia yet included exceptions. The lift axle policy is as follows:

> "A person must not, without a permit, drive or operate on a highway a vehicle or a combination of vehicles in which a control is provided for varying the weight on an axle or group of axles" (BC MTO).

British Columbia also provided information on special specifications for the steering of the lift axle. The regulations only allow self-steer lift axle or liftable booster axle at the very back of the vehicle. The single liftable booster axle is limited to 20,000 pounds if equipped with dual tires and 13,000 pounds for all single tires including Super-Single tires. If permitted to use a lift axle, the control must be an automatic lift device and not controlled by the driver.

Lift axles, without permit, are also prohibited in Saskatchewan. Like British Columbia, exceptions are made for those vehicles that have automatic control systems for the lift axle system and the lift axle auto deploys at appropriate loading. Saskatchewan does not allow supplementary axles to increase payload and the lift axle systems are only lifted from the road surface when the vehicle is empty. Therefore, with the axle lifted it decreases operating costs and wear on pavement. Lift axle systems are only allowed on semi-trailers and full trailers.

While some Canadian provinces presented information that lift axle usage is banned or prohibited, information about exceptions were also included. Although conflicting responses, it can be gathered that lift axle laws are based on province regulations just as state laws in the United States. So while lift axles may be allowed in other provinces, British Columbia has made exceptions for these vehicles that may also need to operate in their province as well.

4.4 Operational Impacts and Considerations

The above sections outlined national and state regulations for Maryland and other states and Canadian Provinces that responded to the survey. With Maryland's lift axle regulations, there is an issue of operational concerns, enforcement, and impact. Given Maryland Laws and regulations for DSVs, there are still some instances where these vehicles are carrying maximum capacities and yet are still in possible violation of other regulations or present some type of harm or impact to the highway system, as discussed below.

As explained in the Code of Maryland Regulations, the dump service truck lift axle can be disengaged for ¼ mile before and after an authorized raise. However, there are instances where after that ¼ mile distance has been traveled, these vehicles are still operating with the lift axle raised when it is supposed to be deployed (as seen in virtual weigh station photographs). Figure 4-8 below shows a dump truck with the lift axle raised when it should to be deployed. The vehicle's single front axle is also overweight.

Figure 4-8 Lift Axle truck from Weigh-In-Motion data

Another concern presented was the usage of state and local roads to avoid Interstate highways where weigh stations would typically be present. Often times, truck operators use state and local roads to avoid these locations when the truck could be in jeopardy of being overweight. The truck may also be in violation of Maryland's lift axle regulation of 13,500 pounds with a 1,500 pound tolerance, thus being in violation of two regulations. Other instances show that at times, dump trucks are fully loaded and may not have enough weight on the lift axle.

While Maryland has regulations to address DSVs equipped with lift axles, there are other trucks operating on Maryland roads that have multiple lift axles that are not regulated because there are no regulations governing the operation of these non-DSVs. As long as that vehicle complies with weight requirements based on the Federal Bridge Formula, then the multiple lift axles do not present a problem. Many questions arise as to whether these same vehicles should have specific restrictions to require regulating weight on the lift axles to ensure that the bulk of the weight is not on the tandem axles. When looking at five-, six- and even seven-axle vehicles that may have two, three or four lift axles, it is only when they are weighed, that the position of the weight can be determined and then the potential damage to highways can be determined using the same technique. But further examining trucks with these configurations could assist in determination of damage to the infrastructure. From virtual WIM data as well as safety initiative data, proper calculations could be completed to look at damage by lift-axle equipped vehicles, mainly DSVs.

Chapter 5: Theoretical Evaluation and Analysis

5.1 Statistical Analysis Results from Virtual Weight Station

The virtual weigh station (VWS) data supplied by SHA was part of a truck inventory database from June 2009 to June 2010. From the data, the Class 7 dump trucks were filtered. As mentioned in the Maryland Traffic Data Findings Section (Section 3.2), the same statistical assumptions were made for each month of data.

Month	Total Dump Trucks	No. Dump Trucks over 50K	No. of Overweight Trucks (> 70K)	No. of Trucks Below Lift Axle Weight	No. of Trucks Exceeding Lift Axle Weight
Jun. 2009	5052	2127	111 (5.2%)	39 (35%)	36 (32%)
Jul. 2009	6701	3255	166 (5.1%)	50 (12%)	52 (31%)
Aug. 2009	5123	2355	180 (7.6%)	74 (41%)	33 (18%)
Sept. 2009	5299	2276	165 (7.2%)	54 (33%)	44 (27%)
Oct. 2009	4867	2091	68 (3.2%)	24 (35%)	28 (41%)
Nov. 2009	3845	1797	46 (2.5%)	22 (48%)	16 (35%)
Dec. 2009	3161	1506	39 (2.5%)	12 (31%)	23 (59%)
Jan. 2010	2500	1136	25 (2.2%)	8 (32%)	15 (60%)
Feb. 2010	1781	573	23 (4.0%)	8 (35%)	12 (52%)
Mar. 2010	3782	1893	68 (3.6%)	34 (50%)	20 (29%)
Apr. 2010	6120	3087	180 (5.8%)	91 (61%)	42 (23%)
May 2010	5472	2473	142 (5.7%)	62 (44%)	38 (27%)
Jun. 2010	5299	2390	204 (8.5%)	88 (43%)	54 (26%)

Table 5-1 Virtual Weigh Station Statistical Results

Table 5-1 shows the break-down for the four-axle dump truck by month and the total number of dump trucks that passed through the VWS. Lighter dump trucks less than 50,000 pounds are discounted in order to obtain the loaded heavy dump trucks that may cause damage to the infrastructure. The third column shows the number of trucks with gross vehicle weights greater than 50,000 pounds. The table also captures how many trucks are overweight which, according to state regulation, is greater than 70,000 pounds. In the last two columns of Table 5-1 the lift axle is isolated and examined from the group of overweight vehicles. The table shows how many overweight vehicles were under or exceeded the mandated lift axle weight.

Based on the data in Table 5-1, most overweight truck traffic occurs during the spring/summer months. Also, there is no relationship in lift axles above or below the mandated weight restriction. Some other important observations are as follows:

- Of those dump trucks over 50,000 pounds, there is an approximate average of 4.85% overweight (> 70 k) trucks per month;
- Of the overweight vehicles, there is an average of 38% of overweight vehicles with the lift axle down force pressure less than mandated restriction; and,
- Of the overweight vehicles, there is an average of 35% of vehicles with the lift axle down force pressure that exceeds the mandated weigh restriction.

One concern that arises when the lift axle weight is below the mandated weight for an overweight vehicle is the gross weight distribution (the gross weight of the truck is over 70,000 pounds, but the lift axle is below the mandated tolerance). If the vehicle is overweight, but the lift axle is under the mandated 13,500 pounds with a 1,500 pound tolerance, then the weight is being distributed to another axle. It is likely that this weight is being transferred to the rear axles and thus, is creating more potential damage from those axles. As for the vehicles that have exceeded the weight regulation for the lift axle, this also creates a concern because there is an increase in the down force pressure of the lift axle which increases the chance of damage to both the bridge structure and the pavement. Overall, the concern is not only with vehicles that exceed weight requirements for the lift axle, but also with those that do not meet the weight requirement to deploy the lift axle, yet have it deployed.

5.2 Statistical Analysis Results from Safety Initiative

In the safety initiative conducted from February 15 to March 20, 2011, at twelve sites across Maryland's Interstate highway system, 531 lift-axle equipped trucks (524 four-axle, 2 five-axle, 3 six-axle and 2 seven-and-up trucks) were stopped, inspected, and various information was collected. A majority (99%) of the vehicles were four-axle trucks, more specifically dump-service vehicles. The average weight of those four-axle trucks was 64,674 pounds and the standard deviation was 12,247 pounds. The standard deviation was high due to the fact that some of the stopped vehicles were empty dump trucks. The trucks were checked to ensure that they were in compliance with weight regulations as well as any other equipment and operational compliance. A summary of the safety initiative data collection is listed below:

A. Four-axle trucks (504 check; 65 non-compliance)

1. COMAR 11.15.27.05 (6 violations) - Violating Lift Axle and Vehicle Design Requirements. These violations could be from various issues. For example, when charging for this violation, the lift axle may exceed the restricted axle weight or not comply with operation restrictions of the lift axle, i.e. the control system standards.
2. COMAR 11.15.27.06 (19 violations) – Not having the lift axle certification from the vehicle manufacturer meeting the conditions of COMAR and US Code of Federal Regulation.
3. COMAR 11.15.27.07 (4 violations) - This section deals with vehicle operation – e.g. not activating the lift axle when fully loaded, or traveling past the ¼ mile distance after turning and not reactivating or deploying the lift axle back down.
4. COMAR 11.15.27.08 (33 violations) - Not having the proper air-pressure on the lift axle.

5. Overweight (2 violations) – No article numbers were cited. The two (2) violations could be overweight on the lift axle or the gross weight. For the purpose of this study, violation of item 3 was assumed.
6. TA13-919i (1 violation) - Transportation Article; Operating registered dump service vehicle in excess of 65,000 lbs. not in compliance with regulations. They could be item 3 or item 4. For statistical purpose, item 3 is assumed here.

B. Five-axle vehicles (2 checked; 0 non-compliance)

C. Six-axle vehicles (3 checked; 1 non-compliance; for statistical purpose, item 3 is assumed.)

D. Seven-axle vehicles (2 checked; 0 non-compliance)

In summary, it can be concluded, the number one violation is not having the proper air-pressure on the lift axle (33 violations or about 6% of all checked vehicles). The next highest is not having the lift axle certification meeting the conditions of COMAR (19 violations or about 4% of all checked vehicles). The third one has to do with vehicle operation – e.g. not activating the lift axle. The research team also added items 5 and 6, plus five-axle vehicle violations to this (8 violations or about 2% of all checked vehicles). The last one has to do with equipment (6 violations or about 1% of all checked vehicles). A bar chart with these four items is shown below in Figure 5.1 to demonstrate various violations (Figure 5-1). The complete survey criteria and results can be found in Appendix B.

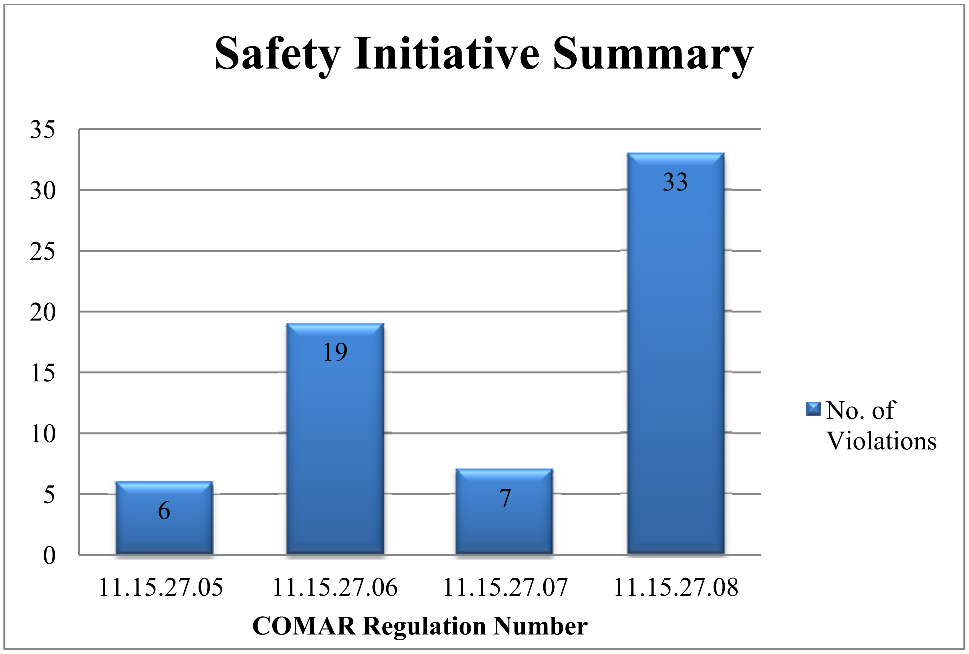


Figure 5-1 Safety Initiative Violation Summary

5.3 Punching Shear Results

Using the outlined approach from Chapter 4, the punching shear approach can be applied to the given nominal truck. Based on the truck configuration of the loading, the punching shear resistance of the slab was calculated with equal total truck loads for tridem (as shown in Figure 5-2) and tandem (with lift axle load equally shared by two rear axles) cases.

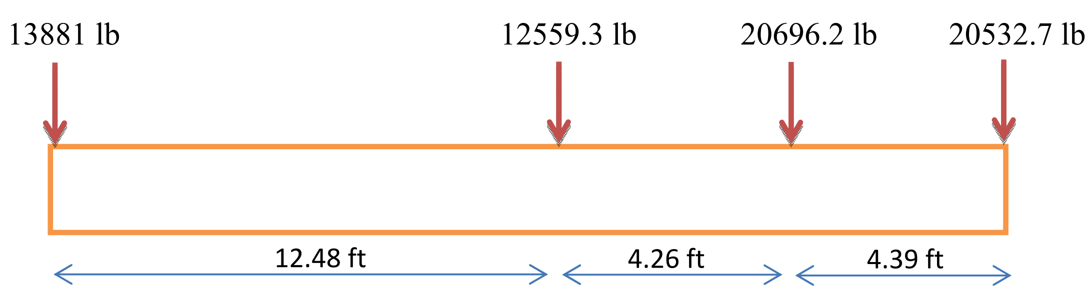


Figure 5-2 Truck Axle Loading Configuration

The following tables (Table 5-2 and Table 5-3) summarize the punching shear capacity for the whole block:

Terms	***Punching Shear Capacity (Tridem)***					
	Depth d_{av}(in)					
d_{av}(in)	7	8	9	10	11	12
length (in)	113.8	113.8	113.8	113.8	113.8	113.8
width(in)	20	20	20	20	20	20
β	5.69	5.69	5.69	5.69	5.69	5.69
$(f_c')^{1/2}$(psi)	63.25	63.25	63.25	63.25	63.25	63.25
b_0(in)	281.6	283.6	285.6	287.6	289.6	291.6
V (kips)	28.08	32.32	36.62	40.97	45.38	49.85

Table 5-2 Punching Shear Capacity for 3-axle Tridem Rear Axle Configuration

Terms	***Punching Shear Capacity(Tandem)***					
	Depth d_{av}(in)					
d_{av}(in)	7	8	9	10	11	12
length (in)	58	58	58	58	58	58
width(in)	20	20	20	20	20	20
β	2.9	2.9	2.9	2.9	2.9	2.9
$(f_c')^{1/2}$(psi)	63.25	63.25	63.25	63.25	63.25	63.25
b_0	170	172	174	176	178	180
V (kips)	21.19	24.51	27.89	31.35	34.87	38.47

Table 5-3 Punching Shear Capacity for Tandem Axle Rear Axle Configuration

Table 5-4 summarizes the punching shear capacity (V) ratio of the comparison of tridem axle configuration versus the tandem axle (last rows of Table 5-2 and Table 5-3):

	Depth d_{av}(in)					
Tridem to Tandem Axle Block Ratio	7	8	9	10	11	12
	1.32	1.32	1.31	1.31	1.30	1.30

Table 5-4 Tridem Axle to Tandem Axle Ratio

As the depth of the slab increases the ratio slowly decreases. However, the change is very small between slab depths of 7 inches to 11 inches, which is commonly used in Maryland bridges.

Table 5-5 considers the difference between three-axle whole block and two-axle whole block (configuration with lift axle raised) in percent loading increments.

% Loading for Lift Axle	Tridem Punching Shear (block)	Tandem Punching Shear (block)	Ratio
20	22.57196541	21.19453	1.06499
40	23.9494009	21.19453	1.12998
60	25.32683638	21.19453	1.19497
80	26.70427187	21.19453	1.259961
100	28.08170736	21.19453	1.324951

Table 5-5 Lift Axle Punching Shear based on Percent Loading

For the punching shear analysis it was found that the punching shear resistance increases as the depth of the slab increases; the higher the shear resistance, the less the possibility of local punching shear failure on bridge decks. However, the punching shear capacity ratio of three-axle to two-axle rear axles remain constant at about 1.32. As the gradual addition of loading on the lift axle, the ratio load carrying capacity varies from 1.06 to 1.32 at 20% to 100% (lift axle deployed and in contact with pavement). Overall, the percent difference between the tandem axle and fully-engaged tridem axle is 33 %.

5.4 Yield Line Results

For the yield line analysis, bending moment was calculated based on the assumptions of the yield line approach. This approach was to determine yield line patterns and to analyze the behavior of the bridge deck transversely. Table 5-6, Table 5-7, and Table 5-8 summarize the analysis.

Load	Girder Spacing	Column Spacing	Λ	Parameters		
p	l_x	l_y	$\lambda = l_y / l_x$	tan a	M^A_x	M^B_x
[lb/ft]	[ft]	[ft]			[lb-ft]	[lb-ft]
6218.29	11.00	24.21	2.20	1.00	31350.54	65558.61
6218.29	10.50	23.50	2.24	1.00	28565.27	60168.57
6218.29	10.00	22.79	2.28	1.00	25909.54	54993.11
6218.29	9.50	22.09	2.32	1.00	23383.36	50033.11
6218.29	9.00	21.38	2.38	1.00	20986.73	45289.56
6218.29	8.50	20.67	2.43	1.00	18719.64	40763.60
6218.29	8.00	19.96	2.50	1.00	16582.10	36456.51
6218.29	7.50	19.26	2.57	1.00	14574.11	32369.78
6218.29	7.00	18.55	2.65	1.00	12695.67	28505.12
6218.29	6.50	17.84	2.74	1.00	10946.78	24864.49

Table 5-6 Tridem Axle Computations for Bending Moments

Load	Girder Spacing	Column Spacing	Λ	Parameters		
p	l_x	l_y	$\lambda = l_y / l_x$	tan a	M^A_x	M^B_x
[lb/ft]	[ft]	[ft]			[lb-ft]	[lb-ft]
12252.44	11.00	19.95	1.81	1.00	61772.71	117185.37
12252.44	10.50	19.24	1.83	1.00	56284.63	107418.15
12252.44	10.00	18.53	1.85	1.00	51051.82	98060.01
12252.44	9.50	17.83	1.88	1.00	46074.27	89111.46
12252.44	9.00	17.12	1.90	1.00	41351.98	80573.11
12252.44	8.50	16.41	1.93	1.00	36884.94	72445.63
12252.44	8.00	15.70	1.96	1.00	32673.17	64729.87
12252.44	7.50	15.00	2.00	1.00	28716.65	57426.79
12252.44	7.00	14.29	2.04	1.00	25015.39	50537.58
12252.44	6.50	13.58	2.09	1.00	21569.39	44063.65

Table 5-7 Tandem Axle Computations for Bending Moments

Girder Spacing(ft)	M^A_x	M^B_x
11.00	1.97	1.79
10.50	1.97	1.79
10.00	1.97	1.78
9.50	1.97	1.78
9.00	1.97	1.78
8.50	1.97	1.78
8.00	1.97	1.78
7.50	1.97	1.77
7.00	1.97	1.77
6.50	1.97	1.77

Table 5-8 Summary of Tandem to Tridem Axle Moment Ratios for Girder Spacing 7-11 ft

From the summary table (Table 5-8) it is evident that the ratio of the moment resistance capacity of the slab is remaining constant with the change in the slab configuration; the higher the moment resistance, the lower the possibility of bending moment failure of the bridge decks. This suggests that the moment capacity mainly depends on the angle of failure plane "a." The ratio of the moment resistance capacity approximately remains same for both M^B_x and M^A_x, (the moments calculated at the edges) so the moment variance in one direction can be calculated from the variance in the other direction. The moments generated in tandem are significantly higher than those generated on tridem; approximately two times higher (1.97). This can be from higher axle loads on the tandem rear axle thus causing a peak in the bending moment diagram at those higher loads and resulting in greater moments for tandem cases.

5.5 Girder Analysis Results

For the bridge girder analysis, the maximum bending moments due to the truck axle loads (with identical distribution and impact factors) on simple span bridges were calculated at various span lengths from 10 feet to 150 feet. Table 5-9 shows the results from the girder bending moment calculations.

S.L. (ft)	Max LL Moment, For LRFD for Tandem Axle (ft-kips)	Max LL Moment, For LRFD for Tridem Axle (ft-kips)	Diff. (%)
10	649.12	554.50	-17.07%
20	992.29	917.28	-8.18%
30	1319.66	1318.88	-0.06%
40	1722.40	1721.65	-0.04%
50	2130.44	2129.72	-0.03%
60	2546.11	2545.40	-0.03%
70	2970.82	2970.13	-0.02%
80	3405.50	3404.83	-0.02%
90	3850.80	3850.14	-0.02%
100	4307.16	4306.51	-0.02%
110	4774.91	4774.27	-0.01%
120	5254.28	5253.65	-0.01%
130	5745.46	5744.83	-0.01%
140	6248.56	6247.94	-0.01%

Table 5-9 Bending Moment Summary for Tandem and Tridem Axle Configuration

The bending moments for the tandem axle cases at 10 feet to 20 feet have the higher percent difference compared to the tridem axle cases. As the span lengths increase the percent difference remained from 0.06% to 0.01%. Figure 5-3 illustrates these values graphically.

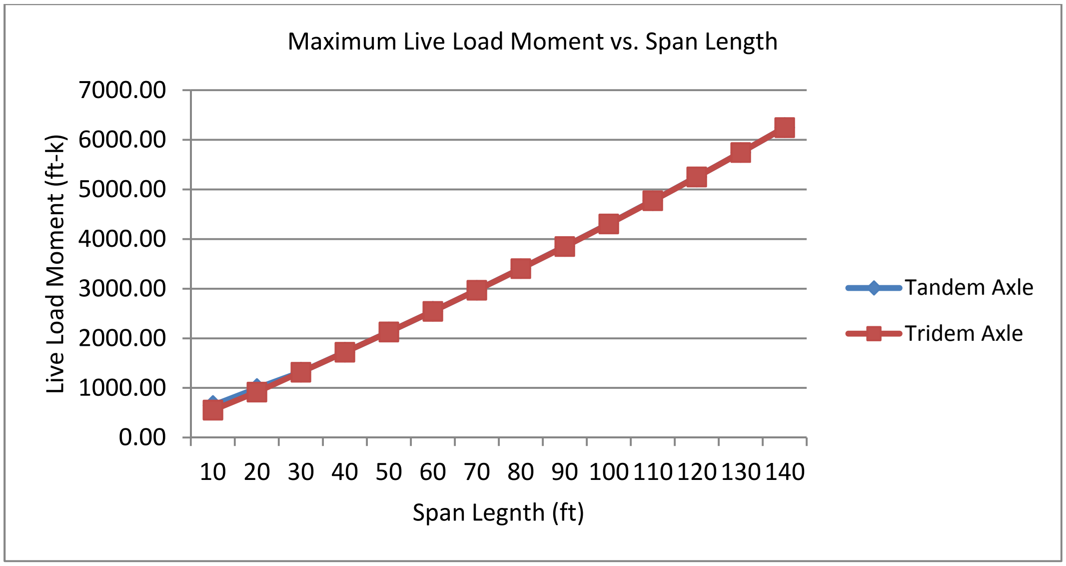


Figure 5-3 Maximum Live Load Moment of the Tandem and Tridem Axle Configurations

From the graph, there is slight variation at the shorter spans (where the tandem axle points are visible). After 20 feet, the tandem and tridem axle are so close in value that their graphs are almost identical.

These results show that the effect of the single unit truck with tandem configuration has more of an effect on bridges with span lengths less than 20 feet. For medium to longer span bridges, the bending moment of the tandem axle truck does not have much difference in the bending moment effect of a truck with the same gross weight but has three rear axles. For those shorter span bridges less than 20 feet, overall the tandem and tridem axle bending moments on the bridge has very little difference. In the case of most highway bridges, the lift axle raised (tandem case) or deployed (tridem case) does not have much effect on the bridge girders if it is a medium or long span bridge structure. It also means that the lift or no lift axle cases with the same gross weight have more influence locally than globally, more on deck than on girders of bridge structures. The position of the lift axle whether deployed or raised has more effect on the bending moments in shorter span bridges than medium to longer span bridges.

5.6 Pavement Analysis Results

There are two major types of pavements: flexible or asphalt pavements, rigid or concrete pavements that were considered. Flexible pavements (Figure 5-4 and Figure 5-5) include the conventional types of layered systems that have higher strength materials near the top where the stresses are high. Rigid pavements (Figure 5-6) are constructed using Portland cement concrete (PCC) and there are four different types of rigid pavements:

- Jointed plain concrete pavement (JPCP)
- Jointed reinforced concrete pavement (JRCP)
- Continuous reinforced concrete pavement (CRCP), and
- Prestressed concrete pavement (PCP)

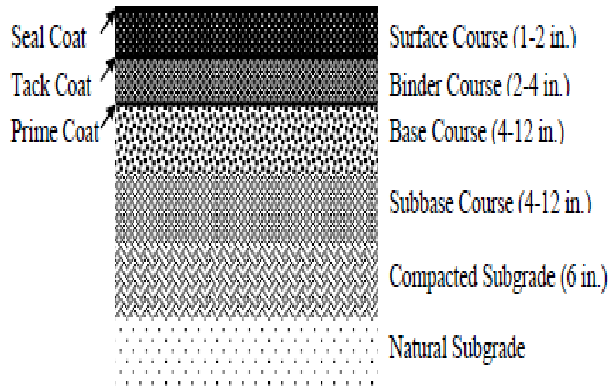


Figure 5-4 Typical Cross Section of Conventional Flexible Pavement (Huang, 2004)

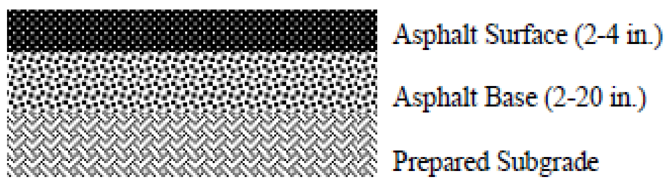


Figure 5-5 Typical Cross Section of Asphalt Pavement (Huang, 2004)

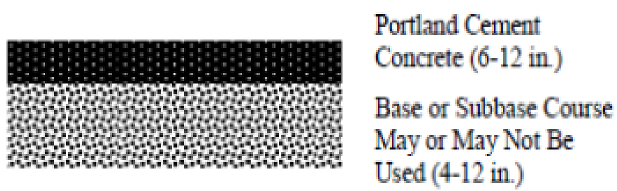


Figure 5-6 Typical Cross Section for Rigid Pavement (Huang, 2004)

The Equivalent Single Axle Load (ESAL) was used to measure potential damage completed by the nominal truck determined in Section 3.3.1 using the VWS data. The calculation was completed for both flexible pavement and rigid pavement. Aside from rigid and flexible pavement, the highway type and specifications were also used. The highway type Structural Number (SN) used in the flexible pavement calculation was calculated based on weighted averages presented in the Maryland Dump Truck report (1993) where the Maryland highway system composition has not dramatically changed.

The following specifications were used for the given highway types:

- State Maintained Roadways SN: 4.42
- County Maintained Roadways SN: 3.5
- Municipal Maintained Roadways SN: 4.5

For the rigid pavement, the depth of pavement is assumed to be nine inches which is typical for pavement. The ESAL calculation was applied to the two main cases (1) Tandem case, where the lift axle is considered to be raised and (2) Tridem case where the lift axle is fully deployed and in contact with the pavement. Tables 5-10 and 5-11 below summarize the results for both flexible pavement and rigid pavement based on those two cases.

Flexible Pavement

Highway Type	**ESAL**	
	Tandem	Tridem
State Maintained	6.50423322	1.996202693
County Maintained	6.74264829	2.020816589
Municipal Maintained	6.52183667	1.993700287

Table 5-10 Flexible Pavement ESAL Calculation Summary

Rigid Pavement

Highway Type	**ESAL**	
	Tandem	Tridem
State Maintained	12.4957436	4.285337702
County Maintained	12.4957436	4.285337702
Municipal Maintained	12.4957436	4.285337702

Table 5-11 Rigid Pavement ESAL Calculation Summary

For all three networks of roadways, the ESAL calculations for flexible pavement were all very close, but highest for county maintained roadways because of the lower structural number, SN, used in Eq. 3-8. Because the depth remains constant, the rigid pavement ESAL calculation does not change in each network. As seen for both flexible and rigid pavement, the three-axle (tandem) truck creates about three times more damage than a four-axle (tridem) truck with a lift axle on equal gross weights. This indicates that having the lift axle down does indeed better distribute the total or gross weight thus decreasing potential damage on the roadway. When the lift axle is not deployed at high gross weights, the weight that is intended to be carried on the deployed lift axle, distributes to the rear axles or tandem axles. This puts more weight on the rear axles and creates more road damage. Figure 5-7 shows the ESAL values for three axle combinations that demonstrate the damage increases as the weight increases. It is again illustrated that there is less damage when the load is distributed among more axles.

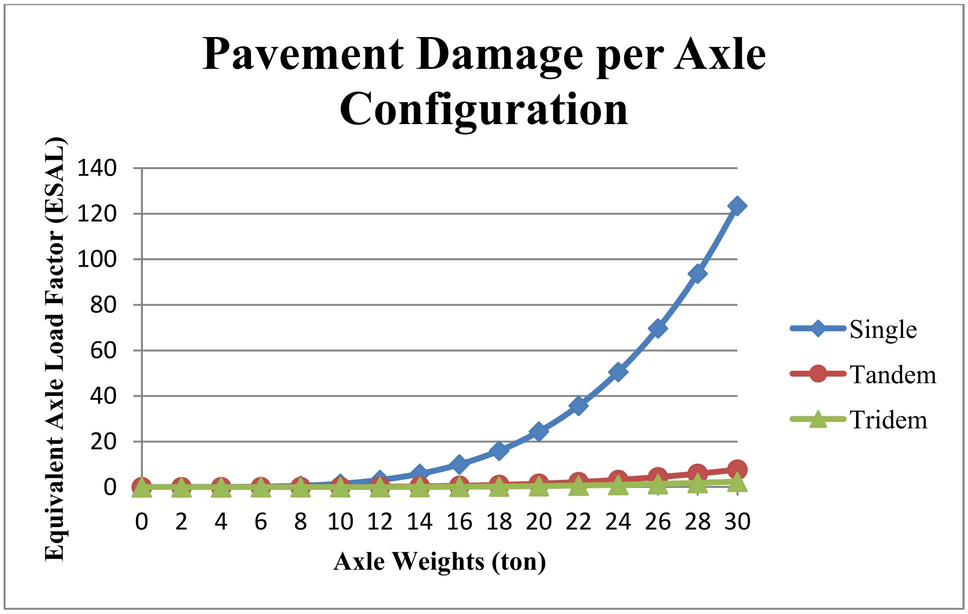


Figure 5-7 Pavement Damage Calculations for Single, Tandem and Tridem Axles

Outside of ESAL life, environmental deterioration of pavement can also be examined. The following graph in Figure 5-8 shows the life of a typical pavement section over a typical 30-year life of a pavement section.

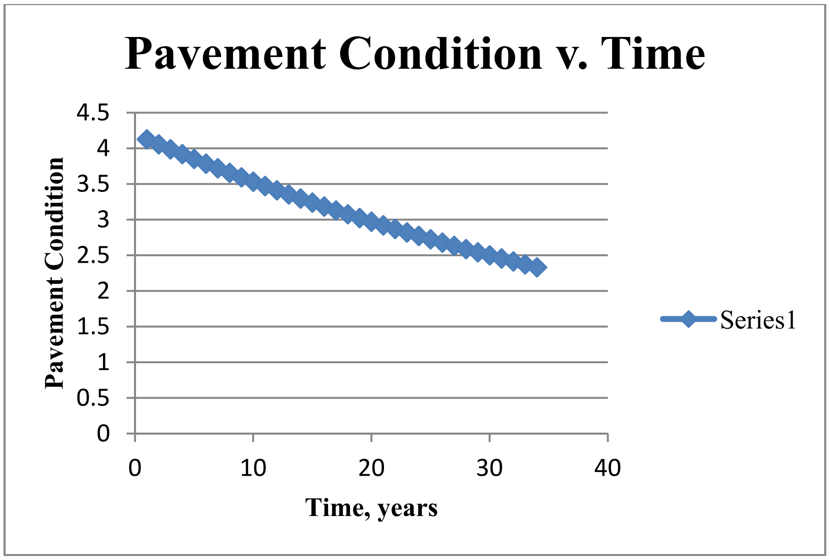


Figure 5-8 Pavement Condition with respect to time for environmental serviceability losses

Just from environmental losses over time, the serviceability of the pavement decreases outside of the repetitive loading and heavy truck traffic.

Chapter 6: Summary and Conclusions

6.1 Summary

The main objective of this research study was to examine the effects of trucks equipped with lift axles on pavement and bridge structures on Maryland roadways. Lift axle surveys were sent out to Departments of Transportation to gain information on truck and lift axle policies nationwide. Analysis approaches based on failure modes were conducted and applied to gain results on their effects on the bridge structure. Three failure modes were identified: punching shear failure of the bridge deck, yield line failure of the bridge deck and bending or shear failures of the bridge girder. Punching shear of a bridge deck of the structure was examined in Section 5.3 to look at the impact of the vertical forces of the single unit truck with tandem or tridem rear axle configuration. The yield line theory approach in Section 5.4 examined the transversal loading effects through bending on the bridge deck. Also, the girder analysis shown in Section 5.5 allowed longitudinal analysis of the structure based on span length. Moreover, potential pavement damage was measured in Section 5.6 based on the axle loading of the truck.

The following summarizes findings:

- The lift axle survey given by the research team showed that there are no uniform regulations for lift axles and each state has their own truck regulations. Some states do not even have laws regulating their usage.
- For Virtual Weigh Station statistical data analysis, the results yielded that there is no relationship between overweight trucks and lift axle weights since there are overweight trucks with lift axle weights that are below as well as exceeds the mandated lift axle weight.

- For the safety initiative data analysis, the results showed that the largest amount of violations with lift-axle equipped trucks were dump service vehicles not meeting air pressure for lift axles. The next highest was not having the lift axle certification meeting the conditions of COMAR.
- For bridge deck shear analysis, the punching shear of the tandem-axle case is 1.32 times larger than the tridem-axle case with the same total axle weights, which means 32% higher potential failed in punching shear compared tandem-axle to tridem-axle cases.
- For the bridge deck moment check, the yield line theory exhibits that the tandem-axle configuration (four-axle truck with lift axle raised) has a bending moment approximately two (2) times greater than that of the tridem-axle configuration, which means based on yield line theory, 100% higher potential failed in deck moment compared tandem- to tridem-axle cases.
- The bridge girder analysis yielded that for short span bridges, the bending moments were higher. But for longer spans over 20 feet, the bending moments for the tandem- and tridem-axle cases were almost identical.
- The pavement analysis showed that for a truck with the lift axle lifted when it was supposed to be deployed, the damage is about three (3) times greater than the damage of a tridem-axle case.

6.2 Conclusions and Future Research

Overall, in each analysis approach the lift axle does have an effect on the behavior of both the bridge structure and the highway pavement. The research found that in almost all of the failure modes, when the lift axle is raised, the weight carried by the lift axle is redistributed to the rear tandem axles. When loading is redistributed to the tandem axles, this essentially puts higher stresses on the structure and thus creates higher moments and shears at critical points along the structure.

Moreover, when trucks are running at the maximum gross vehicle weights, the position of the lift axle becomes very crucial in analysis. Whether the lift axle is raised or deployed at heavy loads has a major impact on potential damage to highways and structures. If trucks are running at maximum weights and the lift axle is not deployed, in accordance with Maryland regulations, this creates not only non-compliance issues, but also distributes a substantial amount of weight to the rear tandems. Even if the truck is not overweight, the redistribution of weight puts more stress on the rear tandem axles which is more harmful to the structure. For example, some lift axles are positioned in front of the rear tandems, and others are positioned behind the rear tandems. Making truck companies accountable for violations and increasing the penalties for those who violate lift axle usage regulations, can help reduce damage to highway infrastructure assets.

There are various findings that were gathered by the research. The most effective control system for lift axles is where the operator of the vehicle does not control the air-pressure of the lift axle and it is the most efficient way in lessening damage to pavement or structures. Increasing the number of lift axles on a vehicle can lead to ancillary issues, such as limiting the ability of enforcement at roadside to weigh these types of vehicles. For example, enforcement officers in roving mode are normally equipped only with six-eight portable scales. If a suspected overweight vehicle has more than four axles, weighing it can become more difficult. It is even more difficult when a multiple lift-axle equipped vehicle is encountered. Although lift axles assist in the redistribution of the gross vehicle weight, if regulated effectively, they can be extremely useful tools to the trucking industry and safer for highway infrastructure. To further investigate the impact of lift axles, more research can be completed on non-DSV with lift axles and their impacts on infrastructure. Although the most popular lift-axle equipped vehicle was the dump truck (based on the survey results), examining nationwide state truck laws as well as their highway truck inventory may assist in determining popularity in lift-axle equipped trucks and determining what trucks are in operation. After more research is completed on non-DSVs with lift axles, recommendations can then be made on regulation and enforcement.

There are numerous factors that contribute to the damage of pavement and bridges including heavy loads and high gross weights. While there is still no direct answer to finding the exact impact of lift axles to highways and bridges, when used properly, they can be a great asset to the highway system. When lift axles are improperly used, they can also cause great damage to the system.

State Axle Weight Limits (in Kips) from DOT Survey Question 2.3								
State	Single		Tandem		Tridem (3-Axle)		Quadrem (4-Axle)	
	Inter-state	State Highways	Inter-state	State Highways	Interstate	State Highways	Interstate	State Highways
Alabama	20	20+10%	34	36+10%	42	42+10%	50	50+10%
Alaska	20	20	38	38	42	42	50	50
Arizona	20	20	34	34	FBF	FBF	FBF	FBF
Arkansas	20	20	34	34	50	50	68	68
California	20	20	34	34	WT	WT	WT	WT
Colorado	20	20	36	40	54	54	N/S	N/S
Connecticut	22.4	22.4	36	36	54	54	N/S	N/S
Delaware	20	20	FBF	FBF	FBF	FBF	FBF	FBF
Florida	22	22	44 (WT)	44(WT)	WT	WT	WT	WT
Georgia	20	23	34	46	34	46	N/A	46
Hawaii	22.5	22.5	34	34	42	43.2	50	50
Idaho	20	20	34	34	42	42	50	50
Illinois	20	18	34	32	WT	WT	WT	WT
Indiana	20	20	34	34	42	42	42	42
Iowa	20	20	34	34	FBF	FBF	FBF	FBF
Kansas	20	20	34	34	42 to 43.5	42 to 43.5	50	50
Kentucky	20	20	34	34	48	48	—	—
Louisiana	20	22	34	37	42	45	50	53
Maine	22	24.2	34	46	42	54	N/S	N/S
Maryland	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Massachusetts	24	24	34	34	36	36	N/S	N/S
Michigan	18	18	WT	WT	WT	WT	WT	WT
Minnesota	20	20	34	34	42	42	50	50
Mississippi	20	20	34	34	42.5	FBF	FBF	FBF
Missouri	20	20	40	40	60	60	60	60
Montana	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Nebraska	20	20	34	34	42	42	50	50
Nevada	20	20	34	34	42	42	—	—
New Hampshire	20	22.4	36/34	44.8	FBF	54/ 60	FBF	N/S
New Jersey	22.4	22.4	34	34	FBF	—	FBF	—
New Mexico	20	21.6	34	34.3	34	48	50	52
New York	22.4	22.4	36	36	FBF	FBF	FBF	FBF
North Carolina	20	20	38	38	FBF	FBF	FBF	FBF
North Dakota	20	20	34	34	FBF	48	FBF	48
Ohio	20	20	34	34	—	—	—	—
Oklahoma	20	20	34	34	FBF	FBF	FBF	FBF
Oregon	20	20	34	34	WT	WT	WT	WT
Pennsylvania	22.4	22.4	38	38	58.4	58.4	73.28	73.28
Rhode Island	22.4	22.4	44.8	44.8	67.2	67.2	89.6	89.6
South Carolina	20	20	40	40	60	60	—	—
South Dakota	20	20	34	34	42	42	—	—
Tennessee	20	20	34	34	FBF	FBF	FBF	FBF
Texas	20	20	34	34	—	—	—	—
Utah	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Vermont	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Virginia	20	20	WT	WT	WT	WT	WT	WT
Washington	20	20	34	34	FBF	FBF	FBF	FBF
West Virginia	20	20	34	34	FBF	FBF	FBF	FBF
Wisconsin	20	20	34	34	42	42	50	50
Wyoming	20	20	36	36	42	42	FBF	FBF

*N/S = Not specified; WT = Weight table; N/R = No response.

Table A.1 State Axle Weight Limits from NCHRP Report 575

Question 2.5: For these SHVs, specify below how your agency grants exemptions from certain federal weight limits.													
DOT	**Single Axle**			**Tandem Axle**			**Federal Limit B Formula**			**Gross Weight (80 Kips)**			
	Yes	No	If yes, up to (Kips)	Yes	No	If yes, up to (Kips)	Yes	No	If yes, specify	Yes	No	If yes, up to (Kips)
Arkansas		X		X		36.5	X		36.5		X	
Idaho		X		X		37.8	X		Exceeds FBF by up to 26% for certain axle comb		X	
Illinois		X			X			X			X	
Iowa		X		X			X		Up to 20 kips per axle	X		
Kansas	X			X			X			X		85.5
Minnesota		X			X		X				X	
Mississippi		X			X			X			X	
New Jersey	X		No Limit	X		No limit	X		Limit is applied only on GVW and tire pressure	X		
New Mexico	X		21.6	X		34.3		X			X	
North Carolina	X		23.5	X		44	X			X		90
North Dakota		X			X		—	—	Allow 3 or 4 axle group to 51000#	—	—	—
Ohio	X		10%	X		10%	X		10%	X		10%
Oklahoma		X			X		X				X	
Texas		X		X		46	X				X	
Washington	X		24	X		43	X			—	—	
Wisconsin		X		X		45	X			X		155
Total	**6**	**10**		**11**	**5**		**12**	**3**		**6**	**8**	

Table A.2 Specialized Hauling Vehicle Weight Exemption Summary

By NCHRP Report 575

DOT	Truck Designation	Total Axle Spacing *L* (ft.)	No. of Axles *N*	GVW (Kips)	FBF Gross Weight Limit (Kips)	Satisfies FBF Gross Weight Limit?	Satisfies FBF Axle Weight Limit?
Alabama	Tandem Axle	19	3	59.0	50.3	No	No
	Tri-Axle	19	4	75.0	54.7	No	No
	Concrete Truck	18	3	66.0	49.5	No	No
Arkansas	T3	12	3	45.0	45.0	Yes	Yes
	T4	18	4	62.0	52.7	No	No
	T3S2	24	5	80.0	63.0	No	Yes
Connecticut	Construction Vehicle	18.2	4	76.5	54.1	No	No
Delaware	DE 2	10	2	40.0	40.0	Yes	Yes
	DE 3 Inter-State	16.83	3	54.0	48.6	No	No
	DE 3	16.83	3	70.0	48.6	No	No
	DE 4	17	4	73.0	52.9	No	No
Florida	SU2	13	2	34.0	43.0	Yes	No
	SU3	15.17	3	66.0	47.4	No	No
	SU4	18.34	4	70.0	53.7	No	No
	C3	30	3	56.0	58.5	Yes	No
Georgia	H20-MOD	14	2	43.0	44.0	Yes	No
	Type 3	19	3	66.0	50.3	No	No
Idaho	Type 3	14	3	54.0	46.5	No	No
Illinois	Type 3	16	3	44.0	48.0	Yes	Yes
	Type 3-S1	28	4	58.5	60.8	Yes	Yes
	Type 3-S2	30	5	72.0	66.8	No	Yes
Kentucky	Type 1	14	2	40.0	44.0	Yes	No
	Type 2	16	3	56.7	48.0	No	No
	Type 3	20	4	73.5	55.3	No	No
	Type 4	34	5	80.0	69.3	No	No
Michigan	No 1	9	2	33.4	39.0	Yes	Yes
	No.2	12.6	3	41.4	45.4	Yes	Yes
	No.3	16	4	54.4	52.7	No	Yes
	No.4	19.6	5	67.4	60.2	No	No
	No.5	28	6	78.0	70.8	No	No
	No.9	18	3	51.4	49.5	No	Yes
	No. 10	21.6	4	59.4	56.3	No	Yes
	No.11	30.6	5	77.4	67.1	No	Yes
Minnesota	Type 3	14	3	48.0	46.5	No	Yes
Mississippi	Concrete Truck	16	3	60.0	48.0	No	No
	HS-Short	30	5	80.0	66.8	No	No

Table A.3 NCHRP Report 575 with FBF-B State Posting Checks (I)

DOT	Truck Designation	Total Axle Spacing *L* (ft.)	No. of Axles *N*	GVW (Kips)	FBF Gross Weight Limit (Kips)	Satisfies FBF Gross Weight Limit?	Satisfies FBF Axle Weight Limit?
New Hampshire	Two-Axle Truck	14	2	33.4	44.0	Yes	No
	Three-Axle Truck	16	3	55.0	48.0	No	No
	Four-Axle Truck	18	4	60.0	54.0	No	No
North Carolina (Interstate Traffic)	SH	14	2	25.0	44.0	Yes	No
	S3A	13	3	45.5	45.8	Yes	No
	S3C	15	3	43.0	47.3	Yes	No
	S4A	17	4	53.5	53.3	Yes	No
	S5A	21	5	61.0	61.1	Yes	No
	S6A	25	6	69.0	69.0	Yes	No
	S7A	34	7	80.0	79.8	Yes	No
	S7B	29	7	77.0	76.9	Yes	No
	T4A	22	4	56.5	56.7	Yes	No
	T5B	26	5	64.0	64.3	Yes	No
	T6A	30	6	72.0	72.0	Yes	No
	T7A	34	7	80.0	79.8	Yes	No
	T7B	34	7	80.0	79.8	Yes	No
North Carolina (Except Interstate Traffic)	SH	14	2	25.0	44.0	Yes	No
	S3A	13	3	50.1	45.8	No	No
	S3C	15	3	43.0	47.3	No	No
	S4A	17	4	58.9	53.3	No	No
	S5A	21	5	67.1	61.1	No	No
	S6A	25	6	75.9	69.0	No	No
	S7A	34	7	80.0	79.8	No	No
	S7B	29	7	80.0	76.9	No	No
	T4A	22	4	62.2	56.7	No	No
	T5B	26	5	70.4	64.3	No	No
	T6A	30	6	79.2	72.0	No	No
	T7A	34	7	80.0	79.8	No	No
	T7B	34	7	80.0	79.8	No	No
Ohio	2F1	10	2	30.0	40.0	Yes	Yes
	3F1	14	3	46.0	46.5	Yes	Yes
	4F1	18	4	52.0	54.0	Yes	Yes
Pennsylvania	ML80	18	4	73.3	54.0	No	No
	TK527	34	7	80.0	80.0	Yes	No
South Dakota	Type 3	16	3	48.0	48.0	Yes	Yes
Tennessee	TN4	19.17	4	74.0	54.8	No	No
Texas	Single Delivery Truck	17	2	38.0	47.0	Yes	No
	Concrete Truck	14	3	69.0	51.0	No	No
Virginia	Single-Unit Truck	24	3	54.0	51.8	No	Yes

Table A.4 Continuation of NCHRP Report 575 with FBF-B State Posting Checks (II)

DOT	Truck Designation	No. of Axles	Total Spacing	Truck Weight (Kips)	FBF Limit for Gross Wt (K)	Excess over FBF Limit (K)
Alabama	Tandem Axle	3	19.00	59.00	50.30	8.70
	Concrete Truck	3	18.00	66.00	49.50	16.50
Delaware	DE 3 Interstate	3	16.83	54.00	48.60	5.40
	DE 3	3	16.83	70.00	48.60	21.40
Florida	SU3	3	15.17	66.00	47.40	18.60
Georgia	Type 3	3	19.00	66.00	50.30	15.70
Idaho	Type3	3	14.00	54.00	46.50	7.50
Kentucky	Type 2	3	16.00	56.70	48.00	8.70
Michigan	No. 9	3	18.00	51.40	49.50	1.90
Mississippi	Concrete Truck	3	16.00	60.00	48.00	12.00
New Hampshire	Three-Axle Truck	3	16.00	55.00	48.00	7.00
Texas	Concrete Truck	3	14.00	69.00	51.00	18.00
Virginia	Single-Unit Truck	3	24.00	54.00	51.80	2.20
Alabama	Tri-Axle	4	19.00	75.00	54.70	20.30
Arkansas	T4	4	18.00	62.00	52.70	9.30
Connecticut	Construction Vehicle	4	18.20	76.50	54.10	22.40
Delaware	DE 4	4	17.00	73.00	52.90	20.10
Florida	SU4	4	18.34	70.00	53.70	16.30
Kentucky	Type 3	4	20.00	73.50	55.30	18.20
Michigan	No. 3	4	16.00	54.40	52.70	1.70
	No. 10	4	21.50	59.40	56.30	3.10
New Hampshire	Four-Axle Truck	4	18.00	60.00	54.00	6.00
North Carolina	S4A	4	17.00	58.85	53.30	5.55
Pennsylvania	ML80	4	18.00	73.30	54.00	19.28
Tennessee	TN4	4	19.17	74.00	54.80	19.20
Arkansas	T3S2	5	24.00	80.00	63.00	17.00
Illinois	3-S2	5	30.00	72.00	66.80	5.20
Kentucky	Type 4	5	34.00	80.00	69.30	10.70
Michigan	No. 4	5	19.50	67.40	60.20	7.20
	No. 11	5	30.50	77.40	67.10	10.30
Mississippi	HS-Short	5	30.00	80.00	66.80	13.20
North Carolina	S5A	5	21.00	67.10	61.10	6.00
Michigan	Concrete Truck No. 5	6	28.00	78.00	70.80	7.20
North Carolina	S6A	6	25.00	75.90	69.00	6.90

Table A.5 NCHRP Summary of State Posting that Exceed the Federal B G.W.L

G.W.L (Gross Weight Limit)

4 Axle Vehicle								
Station	Date	MD DSV REG	Overweight	GVW	COMAR Compliance	Violation		
		(Y/N)	(Y/N)	(lbs)	(Y/N)	(COMAR Reg. #)		
Blubaugh	21-Feb	Y	N	70000	Y			
		N	N	55000	Y			
		N	N	70000	Y			
	24-Feb	N	N	70000	N	No certif.		
		N	N	70000	Y			
		Y	N	70000	Y			
	1-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
	3-Mar	Y	N	70000	N	11.15.27.08.a		
	7-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
	14-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
	15-Mar	Y	Y	70000	N	11.15.27.08F3		
		Y	Y	70000	N	11.15.27.08F3		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
	17-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
Dean	23-Feb	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	N	11.15.2708F1		
	24-Feb	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
	4-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			

		Y	N	70000	Y			
	7-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	TA13-919i		
	9-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	Y			
		Y	N	70000	N	11-1527.0(8f3)		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
	11-Mar	Y	N	70000	Y			
		Y	Y	70000	Y	Overweight		
		N	Y	75200	N/A	Overweight		
		Y	N	70000	Y			
		Y	N	70000	N	11.27.15.05A5		
	15-Mar	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	N	11-1527.08F1		
Iman	11-Mar	Y	N	25700	Y			
		Y	N	25000	Y			
		Y	N	69420	Y			
		Y	N	69040	Y			
	12-Mar	Y	N	39060	Y			
		Y	N	60000	Y			
		Y	N	26700	Y			
		Y	N	26000	Y			
		Y	N	26500	Y			
Iman& Pearce	20-Mar	N	N	24000	Y			
		Y	N	27500	Y			
		Y	N	26800	Y			
		Y	N	26900	Y			
		Y	N	26980	Y			
		Y	N	26400	Y			
A. Johnson	4-Mar	N	Y	55000	N			
		N	N	55000	Y			
		N	N	55000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
Barnes& Snyder	9-Mar	Y	N	69500	Y			
		Y	N	69600	Y			

		Y	N	68900	Y			
		Y	N	63700	Y			
Barnes& Rodeheaver	14-Mar	Y	N	43500	Y			
		Y	N	68600	N	11.15.27.08F2		
Barnes& Snyder	15-Mar	Y	N	66500	N	11.15.27.08F1		
		Y	N	60800	Y			
		Y	N	57600	Y			
Barnes& Rodeheaver	17-Mar	Y	N	69600	Y			
		Y	N	68900	Y			
		Y	N	69400	N	11.15.27.05F2		
Barnes& Naples	19-Mar	Y	N	69500	Y			
		Y	N	68400	Y			
		Y	N	64800	Y			
		Y	Y	59400	N	11.15.27.06		
		Y	N	35600	Y			
		Y	N	38900	Y			
		Y	N	54300	Y			
Hyattstown South	18-Mar	Y	N	67300	N	11.15.27.08F3		
		Y	N	69040	Y			
		Y	N	64520	Y			
		Y	N	69040	Y			
		Y	N	69060	Y			
		Y	N	69880	Y			
		Y	N	66440	Y			
		Y	N	68960	Y			
		Y	Y	67760	N	11.15.27.06		
		Y	N	67160	Y			
		Y	N	69540	Y			
		Y	N	69380	Y			
		Y	N	69280	Y			
		Y	N	70220	Y			
		Y	N	68700	Y			
		Y	N	68500	Y			
		Y	N	69680	Y			
		Y	N	69700	Y			
		Y	N	69000	Y			
		Y	N	67400	Y			
		Y	N	69260	Y			
		Y	N	68480	Y			
Arminger	14-Mar	Y	N	59800	Y			
		Y	N	27900	Y			
		Y	N	28200	Y			

		Y	N	27600	Y			
		Y	N	68300	Y			
		Y	N	63900	Y			
		Y	N	27900	Y			
		Y	N	65800	Y			
		Y	N	27600	Y			
New Market Scalehouse	2/15-3/20	Y	Y	65000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	Y	65000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	65000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	Y	70000	N	No cert.		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
New Market Scalehouse	2/15-3/20	Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.06		
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			

		Y	N	65000	Y			
		N	N	58500	Y			
		N	N	53500	Y			
		N	N	64000	Y			
		N	N	54000	Y			
		N	N	46000	Y			
		N	N	70000	Y			
		Y	Y	70000	N	11.15.27.05		
		N	N	58000	Y			
		Y	N	70000	Y			
		N	Y	70000	Y			
		Y	N	60000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	N	11.15.27.07		
		Y	Y	70000	Y			
		Y	N	70000	N	11.15.27.08		
		Y	N	70000	Y			
New Market Scalehouse	2/15-3/20	Y	N	70000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.06		
		Y	N	70000	N	11.15.27.08A		
		Y	Y	70000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	65000	Y			
		Y	N	70000	Y			
		Y	N	65000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	65000	Y			
		Y	Y	70000	N	11.15.27.06		
		Y	Y	70000	N	11.15.27.06		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			

		Y	N	70000	Y			
New Market Scalehouse	2/15-3/20	Y	N	70000	N	11.15.27.06A2		
		Y	N	70000	N	11.15.27.06A2		
		Y	N	70000	N	11.15.27.06A2		
		Y	N	70000	N	11.15.27.06A2		
		Y	N	70000	N	11.15.27.06A2		
		Y	N	70000	N	11.15.27.06A2		
Finzel S.H.	2/15-3/20	Y	N	70000	N			
		Y	N	69000	N			
		Y	N	66640	N			
		Y	N	68800	N			
		Y	N	70000	N			
		Y	N	69160	N			
		Y	N	69640	N			
		Y	N	67500	N			
		Y	N	66040	N			
		Y	N	69200	N			
		Y	N	69400	N			
		Y	N	68980	N			
		Y	N	69700	N			
		Y	N	69800	N			
		Y	N	69560	N			
		Y	N	57460	N			
		Y	N	70000	N			
		Y	N	69860	N			
		Y	N	67960	N			
		Y	N	69180	N			
		Y	N	69500	N			
		Y	N	68420	N			
		Y	N	65800	N			
		Y	N	68580	N			
		Y	N	68800	N			
		Y	N	69940	N			
		Y	N	69740	N			
		Y	N	68660	N			
		Y	N	66600	N			
Finzel S.H.	2/15-3/20	Y	N	64700	N			
		Y	N	69200	N			
		Y	N	69140	N			
		Y	N	68200	N			
		Y	N	68790	N			
		Y	N	68640	N			
		Y	N	69600	N			
		Y	N	69700	N			
		Y	N	68800	N			
		Y	N	69000	N			

		Y	N	68980	N			
		Y	N	69480	N			
		Y	N	29840	N			
		Y	N	27700	N			
		Y	N	69100	N			
		Y	N	70120	N			
		Y	N	69640	N			
		Y	N	69340	N			
		Y	N	69040	N			
		Y	N	69180	N			
		Y	N	69880	N			
		Y	N	69460	N			
		Y	N	69500	N			
		Y	N	68120	N			
		Y	N	27920	N			
		Y	N	69460	N			
		Y	N	69120	N			
		Y	N	28500	N			
		Y	N	27440	N			
Finzel S.H.	2/15-3/20	Y	N	68500	N			
		Y	N	68460	N			
		Y	N	69820	N			
		Y	N	69660	N			
		Y	N	62220	N			
		Y	N	68220	N			
		Y	N	68600	N			
		Y	N	68740	N			
		Y	N	68520	N			
		Y	N	69300	N			
		Y	N	69160	N			
		Y	N	67100	N			
		Y	N	68660	N			
		Y	N	69860	N			
		Y	N	70080	N			
		Y	N	69100	N			
		Y	N	68700	N			
		Y	N	68620	N			
Finzel S.H.	2/15-3/20	Y	N	70000	N			
		Y	N	70000	N			
		Y	N	70000	N			
		Y	N	70000	N			
	2/15-3/20	Y	Y	70000	N	11.15.27.08F3		
		Y	Y	70000	Y			
Parkton S.H.	2/15-3/20	Y	N	52100	Y			
		Y	N	69020	Y			
		Y	N	69160	Y			
		Y	N	69600	Y			

		Y	N	68560	Y			
		Y	N	69920	Y			
		Y	N	69240	Y			
		Y	N	68380	Y			
		Y	N	68460	Y			
		Y	N	68480	Y			
		Y	N	69200	Y			
		Y	N	69200	Y			
		Y	N	69590	Y			
		Y	Y	56900	N	11.15.27.07		
		Y	N	69560	Y			
		Y	N	68900	Y			
		Y	N	68500	Y			
		Y	N	69760	Y			
		Y	N	69360	Y			
		Y	N	68360	Y			
		Y	N	68960	Y			
		Y	N	67700	Y			
		Y	N	68020	Y			
		Y	N	69480	Y			
		Y	N	69280	Y			
		Y	N	68800	Y			
		Y	N	69040	Y			
		Y	N	69180	Y			
		Y	N	67500	Y			
Parkton S.H.	2/15-3/20	Y	N	68500	Y			
		Y	N	67420	Y			
		Y	N	69220	Y			
		Y	N	69240	Y			
		Y	N	68160	Y			
		Y	N	67600	Y			
		Y	N	69060	Y			
		Y	N	69520	Y			
		Y	N	66040	Y			
		Y	Y	69320	N	11.15.27.07		
		Y	N	68200	Y			
		Y	N	66620	Y			
		Y	N	69320	Y			
		Y	N	69380	Y			
		Y	N	69240	Y			
		Y	N	67740	Y			
		Y	N	69140	Y			
		Y	N	69540	Y			
		Y	N	69380	Y			
		Y	N	69420	Y			
		Y	N	67240	Y			
		Y	N	68380	Y			

		Y	N	67860	Y			
Conowingo S.H.	2/15-3/20	Y	N	65140	Y			
		Y	N	70840	Y			
		Y	N	70220	Y			
		Y	N	67060	Y			
		Y	N	70520	Y			
		Y	N	69020	Y			
		Y	N	68140	Y			
		Y	N	71000	Y			
		Y	N	70340	Y			
		Y	Y	69600	N	11.15.27.05		
		Y	N	70800	Y			
		Y	N	67340	Y			
		Y	N	69720	Y			
		Y	N	69660	Y			
		Y	N	68500	Y			
		Y	N	69900	Y			
		Y	N	69580	Y			
		Y	N	24740	Y			
		Y	N	26600	Y			
		Y	N	70100	Y			
		Y	N	68500	Y			
		Y	N	67600	Y			
		Y	N	70300	Y			
		Y	N	70100	Y			
		Y	N	30020	Y			
		Y	N	69360	Y			
		Y	N	70440	Y			
		Y	N	70280	Y			
Conowingo S.H.	2/15-3/20	Y	N	69720	Y			
		Y	N	66480	Y			
		Y	N	27660	Y			
		Y	N	70020	N	11.15.2708F3		
		Y	N	69380	Y			
		Y	N	69360	Y			
		Y	N	68840	Y			
		Y	N	69280	Y			
		Y	N	70780	Y			
		Y	N	56040	Y			
		N	Y	70240	N	11.15.27.05A		
		Y	N	27280	Y			
		Y	N	27440	Y			
		Y	N	41940	Y			
		Y	N	25300	Y			
		Y	N	25800	Y			

		Y	N	58760	Y			
		Y	N	46100	Y			
		Y	N	27060	Y			
		Y	N	27780	Y			
		Y	N	28160	Y			
		Y	N	35420	Y			
		Y	N	25720	Y			
		Y	N	29200	Y			
		Y	N	69680	Y			
		Y	N	26140	Y			
		Y	N	69380	Y			
		Y	N	70820	Y			
		Y	N	69460	Y			
Conowingo S.H.	2/15-3/20	Y	N	69940	Y			
		Y	N	29520	Y			
		Y	N	24040	Y			
		Y	N	70100	Y			
		Y	N	64320	Y			
		Y	N	59600	Y			
		Y	N	25000	Y			
		Y	N	28140	Y			
		Y	N	68500	Y			
		Y	N	68820	Y			
		Y	N	24960	Y			
		Y	N	70440	Y			
		Y	N	25140	Y			
		Y	N	26620	Y			
		Y	N	24920	Y			
		Y	N	67140	Y			
		N	N	63500	Y			
		N	N	69760	Y			
		N	N	65940	Y			
		Y	N	68340	Y			
		Y	N	69720	Y			
		Y	N	68100	Y			
		Y	N	69280	Y			
Upper Marlboro S.H.	2/15-3/20	Y	Y	65000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	Y	70000	N	11.15.27.08A		

		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	Y	65000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	N	65000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.08A		
		Y	Y	70000	N	11.15.27.08A		
		Y	N	70000	Y			
		Y	Y	70000	N	No certif.		
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
Upper Marlboro S.H.	2/15-3/20	Y	N	70000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.06		
		Y	N	70000	N	11.15.27.08A		
		Y	Y	70000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	65000	Y			
		Y	N	70000	Y			
		Y	Y	65000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	65000	Y			
		Y	Y	70000	N	11.15.27.06		
		Y	Y	70000	N	11.15.27.06		
		Y	N	70000	Y			

		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
Upper Marlboro S.H.		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	Y	70000	N	11.15.27.06		
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	Y			
		Y	N	65000	Y			
		N	N	58500	Y			
		N	N	53500	Y			
		N	N	64000	Y			
		N	N	54000	Y			
		N	N	46000	Y			
		N	N	70000	Y			
		Y	Y	70000	N	11.15.27.05		
		N	N	58000	Y			
		Y	N	70000	Y			
		N	Y	70000	Y			
		Y	N	60000	Y			
		Y	Y	70000	Y			
		Y	N	70000	Y			
		Y	N	70000	N	11.15.27.07		
		Y	Y	70000	Y			
		Y	N	70000	N	11.15.27.08		
		Y	N	70000	Y			
			avg=	64674	12246.71	= stddev		
5 Axle Vehicle								
Station	Date	MD REG	No. of Lift Axles	GVW	Overweight	Violation		
		(Y/N)	(0, 1 or 2)	(lbs)	(Y/N)	(COMAR Reg. #)		
Conowingo	2/15-3/20	N	1	80000	N	N		
		N	1	80000	N	N		
6 Axle Vehicle								
Station	Date	MD REG	No. of Lift Axles	GVW	Overweight	Violation		
		(Y/N)	(0, 1, 2 or	(lbs)	(Y/N)	(COMAR Reg. #)		

			3)					
Conowingo	2/15-3/20	Y	1	29220	N	N		
		Y	1	29320	N	N		
Dean	9-Mar		1	80000	Y	Y		
<u>Truck Trailer Combination</u>								
Station	Date	Lift Axle on Trailer or Truck	Total No. of Axles	No. of Lift Axles	GVW	Overweight	Allowed Gross Vehicle Weight	Violation Location
		(Trailer /Truck)	(5, 6, 7, 8, or 9)	(0, 1, 2, or 3)	(lbs)	(Y/N)	(lbs)	(Inter, US, State, Cty)
~~Dean~~	~~9-Mar~~	~~Trailer~~	~~6~~	~~1~~	~~80000~~	~~Y~~	~~80000~~	~~US Route~~
Dean	11-Mar	Trailer	7	2	80000	N	80000	US Route
		Trailer	7	2	80000	N	80000	US Route
Tractor Trailer Combination								
Station	Date	Lift Axle on Trailer or Truck	Total No. of Axles	No. of Lift Axles	GVW	Overweight	Allowed Gross Vehicle Weight	Violation Location
		(Trailer /Truck)	(5, 6, 7, 8, or 9)	(0, 1, 2, or 3)	(lbs)	(Y/N)	(lbs)	(Inter, US, State, Cty)

Lift Axle Survey Results

1. Does your state currently utilize its grandfathered rights for Interstate axle and gross weight limits?			
State	Yes	No	Comments
AK		x	
AL		x	
AZ		x	
DC	x		
GA		x	
IN	x		
IA		x	
KS	x		
LA	x		
MD	x		
MA		x	
MI	x		
MN		x	
MO		x	
NE		x	
NV	x		
NH		x	
NY	x		
NC	x		
OH		x	
OR	x		
PA	x		
SD	x		
TN		x	
UT	x		
VA		x	
WA		x	
WY	x		

2. Does your state comply with the Federal Mandated Federal Bridge Formula B(FBF-B) on your interstates?			
State	Yes	No	Comments
AK	x		
AL	x		
AZ	x		
DC	x		
GA	x		
IN	x		
IA	x		
KS	x		
LA	x		
MD	x		
MA	x		
MI	x		
MN	x		
MO	x		
NE	x		
NV	x		
NH	x		
NY		x	
NC	x		
OH	x		
OR	x		
PA	x		
SD	x		
TN	x		
UT	x		
VA	x		
WA	x		
WY	x		

3. Does your state comply with the Federal Mandated FBF-B bridge formula on your other highways?			
State	Yes	No	3a. If not please briefly explain the max gross weight for those respective highways?
AK	x		6axle and 10% scale tolerance for all weights
AL		x	
AZ	x		
DC	x		
GA	x		Only any lift axle done manually outside the truck.
IN	x		
IA	x		
KS	x		Except for those carriers who have a grandfathered exemption
LA		x	Max gross weight for a tractor trailer w/ tandem is 80,000 lbs.
MD	x		Provisions: TA, Title 24, §108, and §109
MA	x		
MI	x		
MN	x		Except for a few divisible load commodities under permit
MO		x	FBF but grants add. 2K lbs, 80K lbs except in 5 commercial zone
NE	x		Only up to 7 axles at 95,000lbs
NV	x		
NH	x		
NY		x	State highways also allow use of NYSDOT permitted weights
NC		x	Max 38K lbs for tandems and 10% tolerance above FBF on road
OH		x	80K lbs but use different formula other than FBF
OR		x	105,000lbs maximum-extend weight heavy haul weights vary.
PA	x		
SD	x		SD has no weight limits. On Interstate permit only for over 80K trucks.
TN		x	
UT	x		UT permits up to 129,000 lbs
VA	x		
WA	x		
WY		x	http://legisweb.state.wy.us

4. How Often is information from weight station records reviewed/analyzed?					
State	Weekly	Monthly	Quarterly	Annually	Comments
AK		x			
AL		x			
AZ	x				
DC		x			
GA				x	
IN				x	
IA		x			
KS		x			
LA				x	
MD		x			
MA					
MI					
MN		x			
MO			x		
NE		x			
NV	x				
NH		x			
NY			x		
NC	x				
OH				x	
OR	x				
PA		x			
SD					
TN				x	
UT	x				
VA	x				
WA		x			
WY					

5. Are your state weigh stations equipped with proper equipment to weigh multiple axle/multiple lift axle vehicles?					
State	Yes (Both)	Multiple fixed axles	Single Lift Axles	Unsure	Comments
AK	x				
AL	x				
AZ	x				
DC		x			
GA					
IN	x				
IA	x				
KS	x				
LA	x				
MD	x				
MA				x	
MI	x				
MN	x				
MO	x				
NE	x				
NV	x				
NH	x				
NY	x				
NC	x				
OH		x			
OR	x				
PA	x				
SD	x				
TN	x				
UT	x				
VA	x				
WA	x				
WY	x				

6. Does your state use a certain type of computer software to keep records of truck weights/characteristics?			
State	Yes	No	6a. If yes, then please include the name of the program.
AK	x		In house program
AL		x	
AZ	x		Unsure
DC		x	
GA	x		OTIS, a program developed in house
IN		x	
IA		x	
KS	x		Tradas: used for storage and analysis of in-motion scale records
LA		x	
MD	x		Maryland 24-1 program captures overweight violations
MA		x	
MI			
MN	x		
MO		x	A program Is in Use
NE	x		
NV	x		Unsure
NH	x		Tradas
NY		x	Microsoft Excel, Cardinal Scales Weigh Station Software
NC	x		
OH		x	
OR	x		
PA		x	MCSEnforcement (Suite of applications)
SD	x		
TN		x	Truck weights and characteristics are analyzed at WIM sites
UT		x	
VA	x		
WA		x	
WY		x	

7. What ratio best describes the number of overweight trucks annually statewide?						
State	0-5%	5-10%	10-20%	Over 25%	Unsure	Comments
AK	x					
AL	x					
AZ					x	
DC				x		
GA		x				
IN	x					
IA	x					
KS		x				
LA	x					
MD	x					
MA		x				
MI					x	
MN					x	
MO		x				
NE	x					
NV	x					
NH					x	
NY					x	
NC					x	
OH					x	
OR	x					
PA	x					
SD					x	
TN						
UT	x					
VA	x					
WA		x				
WY	x					

8. Does your state have enforcement personnel assigned to conduct roving operations weighing trucks with portable scales away from fixed scales?			
State	Yes	No	Comments
AK	x		
AL	x		
AZ	x		
DC	x		
GA	x		
IN	x		
IA	x		
KS	x		
LA	x		
MD	x		
MA	x		
MI	x		
MN	x		
MO	x		
NE	x		
NV	x		
NH	x		
NY	x		
NC	x		
OH	x		
OR	x		
PA	x		
SD	x		
TN	x		
UT	x		
VA	x		
WA	x		
WY	x		

9. Are you aware of instances where enforcement personnel have encountered vehicles equipped with multiple lift axles where they were unable to weigh them due to not having sufficient number of portable scales?			
State	Yes	No	9a. If yes, then please include the name of the program.
AK		x	
AL		x	
AZ		x	
DC		x	
GA		x	
IN	x		Not often-most crews have 4-6 portable scales assigned
IA	x		The frequency has increased over the last several years.
KS	x		Rarely
LA		x	
MD		x	
MA		x	
MI		x	
MN		x	
MO		x	
NE		x	
NV		x	
NH	x		A rough estimate would be 35% of the time
NY	x		It is unknown how often this occurs
NC	x		Unable to provide number of occurrences
OH	x		Records not kept
OR		x	
PA		x	
SD		x	
TN	x		This is rare. Maybe 6 times a year
UT		x	
VA		x	
WA		x	
WY		x	

10. Are there state regulations for multi-axle trucks?			
State	Yes	No	10a. If yes, do the gross weights exceed federal standards?
AK	x		No
AL		x	No
AZ	x		No
DC	x		No
GA		x	n/a
IN	x		Yes on heavy duty highways
IA	x		No
KS	x		Yes
LA	x		No
MD	x		Yes
MA	x		No
MI	x		No
MN	x		No
MO	x		No
NE	x		No
NV		x	
NH	x		Yes
NY	x		Yes
NC	x		Yes
OH		x	
OR	x		Yes
PA		x	No
SD	x		No
TN	x		No
UT	x		Yes
VA		x	
WA	x		No
WY	x		Yes

11. Are there any states axle suspension requirements?			
State	Yes	No	11a. If yes, please briefly explain.
AK		x	
AL		x	
AZ			
DC		x	
GA			
IN		x	
IA		x	
KS		x	
LA	x		Air Pressure regulator must be outside the cab of the vehicle
MD	x		Only in context they be in safe operating condition.
MA		x	
MI		x	
MN		x	
MO	x		FMCSR Parts 390-399 of Title 49 and MO State Chapter 307.400
NE		x	
NV		x	
NH		x	
NY		x	
NC		x	Axle needs to be firmly attached to the vehicle.
OH		x	
OR	x		Lift axle(incl. axles tires brakes) must be able to carry load
PA		x	
SD			
TN		x	
UT	x		Attached Reference
VA		x	
WA		x	
WY	x		http://legisweb.state.wy.us

12. Based on the ranges below, how much do overweight vehicles contribute to the deterioration of pavement and state roadways?					
State	0-20%	20-40%	More than 50%	Unsure	Comments
AK	x				
AL		x			
AZ				x	
DC				x	
GA		x			
IN				x	
IA				x	
KS					
LA				x	
MD				x	
MA				x	
MI				x	
MN				x	
MO			x		
NE				x	
NV				x	
NH				x	
NY				x	
NC				x	
OH				x	
OR				x	
PA				x	
SD				x	
TN				x	
UT					
VA				x	
WA				x	
WY				x	

13. Based on ranges below, how much do overweight vehicles contribute to deterioration of the bridge deck?					
State	0-20%	20-40%	More than 50%	Unsure	Comments
AK	x				
AL		x			
AZ				x	
DC				x	
GA		x			
IN				x	
IA				x	
KS					
LA			x		
MD				x	
MA				x	
MI				x	
MN				x	
MO			x		
NE				x	
NV				x	
NH				x	
NY				x	
NC				x	
OH				x	
OR				x	
PA				x	
SD				x	
TN				x	
UT					
VA				x	
WA		x			
WY				x	

14. Does your state have specific lift axle regulations?				
State	Yes	Yes, Banned	No	Comments
AK	x			
AL			x	
AZ			x	
DC			x	
GA		x		
IN			x	
IA	x			
KS			x	
LA	x			
MD	x			
MA			x	
MI			x	
MN	x			
MO			x	
NE	x			
NV			x	
NH			x	
NY	x			
NC			x	
OH			x	
OR	x			
PA	x			
SD	x			
TN			x	
UT	x			
VA			x	
WA			x	
WY	x			

14a. Does your state's lift axle regulations adhere to state registered vehicles only or foreign vehicles as well?			
State	State Registered Vehicles	State and Foreign Vehicles	Comments
AK		x	
AL		x	
AZ		x	
DC			
GA		x	
IN			
IA		x	
KS			
LA		x	
MD	x		
MA			
MI			
MN		x	
MO		x	
NE		x	
NV		x	
NH			
NY		x	
NC			
OH			
OR		x	
PA		x	
SD		x	
TN		x	
UT		x	
VA			
WA		x	
WY		x	

15. Select the following statement that best fits the description of your state's lift axle regulations.				
State	Permit and Approval	Fixed Axle Regulation	Axle Config.	Comments
AK		x		
AL		x		
AZ		x		
DC				
GA		x		
IN			x	
IA		x		
KS				
LA			x	
MD				
MA				
MI				
MN		x		
MO			x	
NE			x	
NV				
NH				
NY		x		
NC				
OH				
OR			x	
PA			x	
SD		x		
TN			x	
UT			x	
VA			x	
WA			x	
WY			x	

Answer Choices
1. Permit or approval is required for usage
2. Lift axles are to meet the Federal governed fixed axle regulations
3. Usage allowed based on specific axle configuration regulation/specification

16. Does your state have any lift axle steering or equipment specifications?			
State	Yes	No	16a. If yes, then please briefly explain.
AK	x		17 AAC 25.017., 17 AAC 25.320, AAC 25.015(a)
AL		x	
AZ		x	
DC		x	
GA	x		Applies to lift axles that must be manually engaged outside of the cab.
IN		x	
IA		x	
KS			
LA		x	
MD		x	
MA		x	
MI			
MN	x		Pressure adjusting device must be out of the reach of the driver.
MO	x		This type of equipment is held to the same standard as any other axle
NE		x	
NV		x	
NH		x	Dump trucks with steerable lift-axles in front of tandem axles.
NY	x		Only for permitted operation, lift axles must be steerable or trackable
NC		x	
OH			
OR	x		Operating over 80K, control shall not be accessible from the cab.
PA		x	
SD		x	
TN		x	
UT	x		Most cases lift axles must steer
VA		x	
WA	x		The axle must be self steering with exceptions.
WY		x	

17. Does your state have specific lift axle configuration specifications?			
State	Yes	No	17a. If yes, then please briefly explain.
AK		x	
AL		x	
AZ		x	
DC		x	
GA	x		
IN		x	
IA		x	
KS			
LA		x	
MD		x	
MA		x	
MI			
MN		x	
MO	x		Lift axles could be considered as single axles or a grouping of axles
NE	x		Must carry 8% of gross load or 8000 lbs whichever is the least.
NV		x	
NH		x	
NY		x	
NC		x	
OH			
OR		x	
PA		x	
SD	x		Refer to SDCL 32-22-57.1 and Administrative Rule 70:03:01:85
TN			
UT	x		
VA		x	
WA		x	
WY		x	

18. Select which statement best describes the specifications of the control system for retraction and deployment of the lift axle trucks as allowed by your state's regulations.				
State	Choice 1	Choice 2	Choice 3	Comments
AK	x			
AL	x			
AZ		x		
DC			x	
GA		x		
IN			x	
IA	x			
KS				
LA		x		
MD	x			
MA			x	
MI				
MN		x		
MO		x		
NE			x	
NV			x	
NH	x			
NY		x		
NC			x	
OH				
OR	x			
PA	x			
SD	x			
TN			x	
UT		x		
VA			x	
WA	x			
WY			x	

<u>Answer Choices</u>

1. The lift axle control system is on the interior of the truck and controlled by the driver
2. The lift axle control system is on the exterior of the truck and controlled by the driver after load has been added or removed to/from the truck.
3. There are current specifications for control of the lift axle.

19. What is the ratio that best describes the number of overweight trucks with lift axles annually statewide?						
State	0-5%	5-10%	10-20%	Over 25%	Unsure	Comments
AK	x					
AL			x			
AZ					x	
DC					x	
GA	x					
IN					x	
IA		x				
KS						
LA					x	
MD					x	
MA					x	
MI						
MN					x	
MO					x	
NE					x	
NV					x	
NH					x	
NY					x	
NC					x	
OH						
OR	x					
PA					x	
SD					x	
TN					x	
UT	x					
VA					x	
WA		x				
WY				x		

20. Has your state completed any research or studies on the usage of lift axle trucks?			
State	Yes	No	20a. If yes, would you be able to send a copy or link to the research reports to ccfu@umd.edu
AK		x	
AL		x	
AZ		x	
DC		x	No
GA		x	
IN		x	
IA		x	
KS			
LA		x	
MD		x	
MA		x	
MI			
MN		x	
MO		x	
NE		x	No
NV		x	
NH		x	No
NY		x	
NC		x	
OH			
OR		x	
PA		x	
SD		x	
TN		x	
UT		x	
VA		x	
WA		x	
WY		x	

21. Are there any plans to research the usage of lift axles or lift axle specifications in your state?					
State	Yes, future	Yes, currently	No	Unsure	Comments
AK			x		
AL			x		
AZ				x	
DC	x				
GA			x		
IN	x				
IA				x	
KS					
LA			x		
MD		x			
MA			x		
MI					
MN				x	
MO				x	
NE				x	
NV			x		
NH			x		
NY				x	
NC				x	
OH					
OR			x		
PA			x		
SD			x		
TN			x		
UT			x		
VA				x	
WA			x		
WY				x	

22. What types of lift axle equipped vehicles are being used on your state highways?	
State	Please briefly explain. Discuss Schematic of trucks and what of loads it hauls.
AK	Concrete Mixers, Tank Trailers, Flat Bed Trailers and some tractors.
AL	Dump trucks are the number one user of lift axles
AZ	4,5 or more axle dump trucks 4,5 or more axle garbage trucks
DC	4/5 Axle Dump trucks.
GA	
IN	
IA	Up to 8 axles dump and concrete trucks
KS	
LA	Liquid tankers/dump body trucks as well as heavy equipment hauling vehicles.
MD	Single unit non-DSV as well as tractor-semi-trailer units with multiple lift axles
MA	
MI	
MN	Dump trucks hauling garbage concrete agricultural products, and timber
MO	Dump trucks, Typical 5-axle tractor/semi-trailer combinations (aggregate)
NE	Straight trucks: 4,5,6,7 / Truck Tractors combos 6, 7, 8,9 etc. hauling dirt & gravel
NV	Every type in the market
NH	Dump trucks, logging trucks and some tractor-trailer units
NY	Pusher or tag axles are allowed w/ lift axle on the tractor, trailer or both.
NC	Dump trucks, concrete trucks, split axle trailers and flat bed building supply trucks.
OH	
OR	Dump truck, tractors, full/semi trailers, log trucks, garbage trucks, cement trucks
PA	4 axle straight trucks & 6 axle combination vehicles
SD	No restriction on type of vehicles allowed to operate with a variable load axle.
TN	3 and 4 axle dump trucks
UT	For Axle dump concrete mixers five axle flat bed (3 axles 2 lifts trailers)
VA	Mostly straight trucks with 3 to 7 axles.
WA	4 axle dump trucks, single trucks with up to 4 lift axles 5 axle Log trucks
WY	All types and configs. hauling loads of divisible and non divisible commodities.

23. Does your state currently record weight data for lift axle equipped vehicles?			
State	Yes	No	Comments
AK	x		
AL		x	
AZ		x	
DC		x	
GA		x	
IN		x	
IA	x		
KS		x	
LA		x	
MD		x	
MA			
MI		x	
MN		x	
MO		x	
NE		x	
NV		x	
NH		x	
NY		x	
NC			
OH	x		
OR		x	
PA		x	
SD		x	
TN		x	
UT		x	
VA		x	
WA		x	
WY		x	

24. Would you be willing to provide additional information in the event the research team has follow-up questions?			
State	Yes	No	Comment
AK	x		
AL	x		
AZ	x		
DC	x		
GA	x		
IN	x		
IA	x		
KS			
LA	x	x	
MD	x	x	
MA	x		
MI			
MN	x		
MO	x		
NE	x		
NV		x	
NH	x		
NY	x		
NC	x		
OH			
OR	x		
PA	x		
SD		x	
TN	x		
UT	x		
VA	x		
WA	x		
WY	x		

25. Would you like a copy of the survey results?			
State	Yes	No	Comments
AK	x		
AL	x		
AZ	x		
DC	x		
GA	x		
IN	x		
IA	x		
KS			
LA	x		
MD	x		
MA	x		
MI			
MN	x		
MO	x		
NE	x		
NV	x		
NH	x		
NY	x		
NC	x		
OH			
OR	x		
PA	x		
SD	x		
TN	x		
UT	x		
VA	x		
WA	x		
WY	x		

Appendix D – Analysis Calculations

Punching Shear Calculations

The following formula calculations have been used for the punching shear calculations.

$$V_c=(1+2/b)*(f_c^{'})^{1/2}*b_0*d_{av}/6$$

Where d_{av} is the average effective depth.

b_0 is the perimeter of the critical section located at a effective depth $0.5d_{av}$.

b is the ratio of the long side to the short side of the concentrated load or the load reaction area.

The ACI code places an upper limit on $)*(f_c^{'})^{1/2}$ of 100 kips.

Note : Assuming standard axle spacing of 4 ft and tire contact area of 20 in width and 10 in length.

fc' (in psi)	4000

For 3 axle

Punching shear capacity for **whole** block

length (in)	113.8	113.8	113.8	113.8	113.8	113.8
width(in)	20	20	20	20	20	20
Beta	5.69	5.69	5.69	5.69	5.69	5.69
sqrt(fc')(psi)	63.25	63.25	63.25	63.25	63.25	63.25
b0(in)	281.6	283.6	285.6	287.6	289.6	291.6
dav(in)	7	8	9	10	11	12
V in (kips)	28.08	32.32	36.62	40.97	45.38	49.85
Net Punching shear in kips	28.08	32.32	36.62	40.97	45.38	49.85

Punching shear capacity for **each individual** block

length (in)	10	10	10	10	10	10
width(in)	20	20	20	20	20	20
Beta	0.5	0.5	0.5	0.5	0.5	0.5
sqrt(fc')(psi)	63.25	63.25	63.25	63.25	63.25	63.25
b0(in)	74	76	78	80	82	84
dav(in)	7	8	9	10	11	12
V in (kips)	27.30	32.04	37.00	42.16	47.54	53.13
Net Punching shear in kips	81.90	96.13	111.00	126.49	142.62	159.38
For individual blocks						
Ratio:	2.92	2.97	3.03	3.09	3.14	3.20

For 2 axle

length (in)	58	58	58	58	58	58
width(in)	20	20	20	20	20	20
Beta	2.9	2.9	2.9	2.9	2.9	2.9
sqrt(fc')	63.25	63.25	63.25	63.25	63.25	63.25
b0	170	172	174	176	178	180
dav(in)	7	8	9	10	11	12
V (kips)	21.19	24.51	27.89	31.35	34.87	38.47
Net Punching shear in kips	21.19	24.51	27.89	31.35	34.87	38.47

length (in)	10	10	10	10	10	10
width(in)	20	20	20	20	20	20
Beta	0.5	0.5	0.5	0.5	0.5	0.5
sqrt(fc')	63.25	63.25	63.25	63.25	63.25	63.25
b0	74	76	78	80	82	84
dav(in)	7	8	9	10	11	12
V (kips)	27.30	32.04	37.00	42.16	47.54	53.13
Net Punching shear in kips	54.60	64.09	74.00	84.33	95.08	106.25
Ratio:	2.58	2.62	2.65	2.69	2.73	

For whole blocks

3axle-2 axle Block Ratio	1.32	1.32	1.31	1.31	1.30	1.30

For individual blocks

3axle-2axle Ratio	1.50	1.50	1.50	1.50	1.50	1.50

Applied average load per axle is **20.5 kips**

Hence the design is safe for punching shear, under given consideration.

% Difference of load capacity of Lift Axle
32.49507044

Note:

The calculations in the following table have been made and can be compared in three basis, and the procedure has been described.

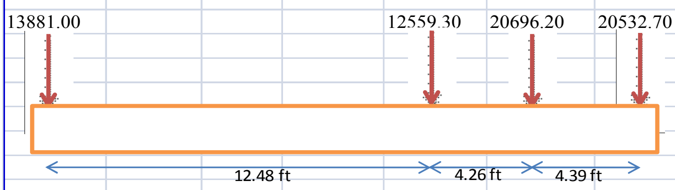
1. Direct division of individual blocks punching shear in 3 axle and 3 axle capacity for percentage loading in 3 i.e liftable axle.
2. The punching shear capacity for whole 2 axle block and % of indivudual punching shear and dividing it by whole 2 axle block capacity.
3. The difference between 3 axle block and 2 axle block as lift axle capacity is applied on % basis, then divide the term by 2 axle whole block.

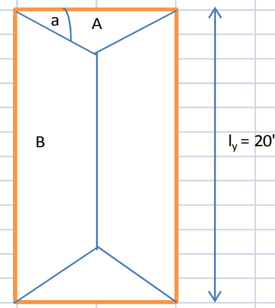
	By individual block method	By whole block method					
%Loading of Lift Axle	**Ratio 3axle/2 axle**	**Individua**	**Whole 2**	**Ratio**	**Whole block, lifta**	**Whole 2**	**Ratio**
20	**1.1**	26.6547	21.1945	**1.25762**	22.57196541	21.1945	**1.06499**
40	**1.2**	32.1149	21.1945	**1.51525**	23.9494009	21.1945	**1.12998**
60	**1.3**	37.5751	21.1945	**1.77287**	25.32683638	21.1945	**1.19497**
80	**1.4**	43.0353	21.1945	**2.03049**	26.70427187	21.1945	**1.25996**
100	**1.5**	48.4955	21.1945	**2.28812**	28.08170736	21.1945	**1.32495**

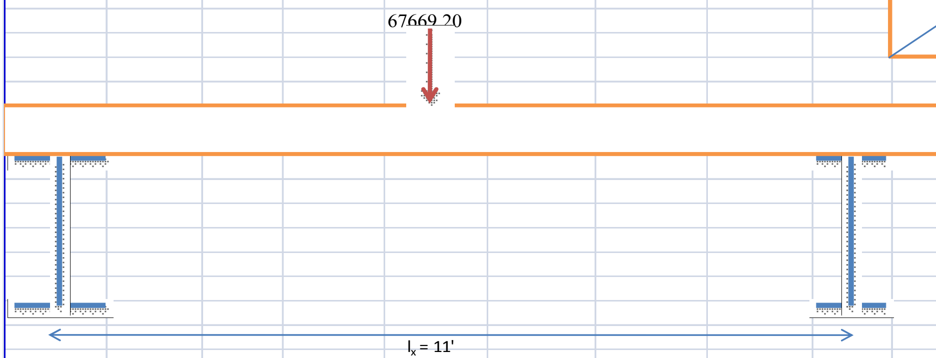
Yield Line Theory Calculations

Condition for all the three axles taking the load.

All axle weights are shown in pounds







lx [ft]	a (deg)
11.00	45.00
10.50	45.00
10.00	45.00
9.50	45.00
9.00	45.00
8.50	45.00
8.00	45.00
7.50	45.00
7.00	45.00
6.50	45.00

a = Angle between a yield line and a principle direction.

l_y = Distance between stiffeners.

l_x = Girder Spacing

$$M_a^A = \frac{p \cdot l_x^2}{24} \tan^2 a \qquad M_a^B = \frac{p \cdot l_x^2}{8} - \frac{p \cdot l_x^2}{12} \frac{\tan a}{\lambda} \quad \text{with } \lambda = \frac{l_y}{l_x}$$

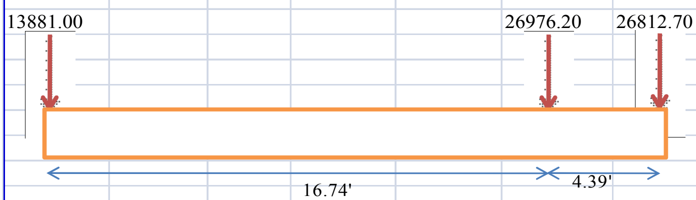
Load p = The three given point loads have been converted into a single equivalent line load.

tan a = $\sqrt{[(1/\lambda)^2 + 3]} - [1/\lambda]$

Load	Girder Spacing	Column Spacing	λ			
p	l_x	l_y	$\lambda = l_y / l_x$	tan a	M^A_x	M^B_x
[lb/ft]	[ft]	[ft]			[lb-ft]	[lb-ft]
6218.29	11.00	24.21	2.20	1.00	31350.54	65558.61
6218.29	10.50	23.50	2.24	1.00	28565.27	60168.57
6218.29	10.00	22.79	2.28	1.00	25909.54	54993.11
6218.29	9.50	22.09	2.32	1.00	23383.36	50033.11
6218.29	9.00	21.38	2.38	1.00	20986.73	45289.56
6218.29	8.50	20.67	2.43	1.00	18719.64	40763.60
6218.29	8.00	19.96	2.50	1.00	16582.10	36456.51
6218.29	7.50	19.26	2.57	1.00	14574.11	32369.78
6218.29	7.00	18.55	2.65	1.00	12695.67	28505.12
6218.29	6.50	17.84	2.74	1.00	10946.78	24864.49

Yield Line Theory Calculations

Condition for two axles taking the load.



a =	Angle between a yield line and a principle direction.
l_y =	Distance between stiffeners.
l_x =	Girder Spacing
Load p =	The two given point loads have been converted into a single equivalent line load.

$$M_a^A = \frac{p \cdot l_x^2}{24} \tan^2 a \qquad M_a^B = \frac{p \cdot l_x^2}{8} - \frac{p \cdot l_x^2}{12} \frac{\tan a}{\lambda} \quad \text{with } \lambda = \frac{l_y}{l_x}$$

tan a = $\sqrt{[(1/\lambda)^2 + 3]} - [1/\lambda]$

Load	Girder Spacing	Column Spacing	λ			
p	l_x	l_y	$\lambda = l_y / l_x$	tan a	M^A_x	M^B_x
[lb/ft]	[ft]	[ft]			[lb-ft]	[lb-ft]
12252.44	11.00	19.95	1.81	1.00	61772.71	117185.37
12252.44	10.50	19.24	1.83	1.00	56284.63	107418.15
12252.44	10.00	18.53	1.85	1.00	51051.82	98060.01
12252.44	9.50	17.83	1.88	1.00	46074.27	89111.46
12252.44	9.00	17.12	1.90	1.00	41351.98	80573.11
12252.44	8.50	16.41	1.93	1.00	36884.94	72445.63
12252.44	8.00	15.70	1.96	1.00	32673.17	64729.87
12252.44	7.50	15.00	2.00	1.00	28716.65	57426.79
12252.44	7.00	14.29	2.04	1.00	25015.39	50537.58
12252.44	6.50	13.58	2.09	1.00	21569.39	44063.65

For the given formulas, we can see that when all the three axles carry the load, the moments generated by the three axles is less than the moments generated when the load is carried by two axles. We can see a significant rise in the moments generated when the lift axle is lifted and not carrying the load.

Moment ratio Tandem axle to Tridem axle

Mxa	**Mxb**
1.97	1.79
1.97	1.79
1.97	1.78
1.97	1.78
1.97	1.78
1.97	1.78
1.97	1.78
1.97	1.77
1.97	1.77
1.97	1.77

Girder Analysis for Bridge Girder Calculations

Maximum Live Load Moment for LRFD Special Cases Tandem Axles

Span Length	10	ft		
Load 1	13.881	kips at	0	ft
Load 3	26.9757	kips at	16.74	ft
Load 4	26.8122	kips at	21.13	ft
Resultant Force	67.6689	kips at	15.04554	
Location of Max IFD	2.5	ft		
LRFD				
	2 Axle Truck			
Moment	148.4375298			ft-k

Span Length	20	ft		
Load 1	13.881	kips at	0	ft
Load 3	26.9757	kips at	16.74	ft
Load 4	26.8122	kips at	21.13	ft
Resultant Force	67.6689	kips at	15.04554	
Location of Max IFD	5	ft		
LRFD				
	2 Axle Truck			
Moment	371.9072798			ft-k

Span Length	30	ft		
Load 1	13.881	kips at	0	ft
Load 3	26.9757	kips at	16.74	ft
Load 4	26.8122	kips at	21.13	ft
Resultant Force	67.6689	kips at	15.04554	
Location of Max IFD	7.5	ft		
LRFD				
	2 Axle Truck			
Moment	611.3770298			ft-k

Maximum Live Load Moment for LRFD Special Cases for Tridem Axles

Span Length	10	ft		
Load 1	13.881	kips at	0	ft
Load 2	12.559	kips at	12.48	ft
Load 3	20.6962	kips at	16.74	ft
Load 4	20.5327	kips at	21.13	ft
Resultant Force	67.6689	kips at	13.84752	ft
Location of Max IFD	2.5	ft		
LRFD				
	3 Axle Truck			Max Moment
Moment	114.569		96.86061	114.569

Span Length	20	ft		
Load 1	13.881	kips at	0	ft
Load 2	12.559	kips at	12.48	ft
Load 3	20.6962	kips at	4.26	ft
Load 4	20.5327	kips at	4.39	ft
Resultant Force	67.6689	kips at	13.84752	ft
Location of Max IFD	5	ft		
LRFD				
	3 Axle Truck			
Moment	317.691548			ft-k

Span Length	30	ft		
Load 1	13.881	kips at	0	ft
Load 2	12.559	kips at	12.48	ft
Load 3	20.6962	kips at	4.26	ft
Load 4	20.5327	kips at	4.39	ft
Resultant Force	67.6689	kips at	13.84752	ft
Location of Max IFD	7.5	ft		
LRFD				
	3 Axle Truck			
Moment	565.1636945			ft-k

Girder Analysis Summary for Various Span Lengths

Maximum Live Load Moment for LRFD

Spacing = 7 ft
Multi-Lane Factor = 1

S.L	Max Moment due to LL, For LRFD			LRFD	
	2 axle	3 axle	Lane (U.D.L)	D.F	IM.F*
10	148.44	114.57	0.00	0.8503	0.33
20	371.91	317.69	0.00	0.7499	0.33
30	611.38	565.16	0.00	0.6973	0.33
40	855.78	855.28	0.00	0.6625	0.33
50	1161.93	1161.43	0.00	0.6369	0.33
60	1484.08	1483.58	0.00	0.6168	0.33
70	1822.23	1821.73	0.00	0.6003	0.33
80	2176.38	2175.88	0.00	0.5865	0.33
90	2546.53	2546.03	0.00	0.5746	0.33
100	2932.68	2932.18	0.00	0.5642	0.33
110	3334.83	3334.33	0.00	0.5549	0.33
120	3752.98	3752.48	0.00	0.5466	0.33
130	4187.13	4186.63	0.00	0.5391	0.33
140	4637.28	4636.78	0.00	0.5323	0.33
150	5103.43	5102.93	0.00	0.5261	0.33

Maximum Live Load Moment for LRFD

Spacing = 7 ft
Multi-Lane Factor = 1

S.L	Max Moment due to LL, For LRFD			LRFD	
	2 axle	3 axle	Lane (U.D.L)	D.F	IM.F*
10	148.44	114.57	0.00	0.8503	0.33
20	371.91	317.69	0.00	0.7499	0.33
30	611.38	565.16	0.00	0.6973	0.33
40	855.78	855.28	0.00	0.6625	0.33
50	1161.93	1161.43	0.00	0.6369	0.33
60	1484.08	1483.58	0.00	0.6168	0.33
70	1822.23	1821.73	0.00	0.6003	0.33
80	2176.38	2175.88	0.00	0.5865	0.33
90	2546.53	2546.03	0.00	0.5746	0.33
100	2932.68	2932.18	0.00	0.5642	0.33
110	3334.83	3334.33	0.00	0.5549	0.33
120	3752.98	3752.48	0.00	0.5466	0.33
130	4187.13	4186.63	0.00	0.5391	0.33
140	4637.28	4636.78	0.00	0.5323	0.33
150	5103.43	5102.93	0.00	0.5261	0.33

Pavement Calculations for Flexible and Rigid Pavements

<u>Flexible Pavement Model:</u> State Maintained Roads

Truck Example 1: Steering Axle		Truck Description			
Lx	13.881	Class	7		
L2	1	No. of Axles	4		
pt	2.5	Gross Weight	67,669		
SN	4.42	Axle Weights:	Axle 1	13,881	lbs
Gt	-0.20091		Axle 2	12,559	lbs
Bx	0.477025		Axle 3	20696.2	lbs
B18	0.569591		Axle 4	20532.7	lbs

Log(Wtx/Wt18) 0.439874

Wt18/Wtx 0.363183 ESALs

When Lx is on a single axle

EALF (Lx/18)^4 0.353666 ESALs

Assuming lift axle is raised		*Assuming lift axle is deployed*	
Truck Example 1: Tridem Axle		Truck Example 1: Tandem Axle	
Lx	53.788	Lx	53.788
L2	3	L2	2
pt	2.5	pt	2.5
SN	4.42	SN	4.42
Gt	-0.20091	Gt	-0.20091
Bx	0.567564	Bx	0.986184
B18	0.569591	B18	0.569591
Log(Wtx/Wt18)	-0.21299	Log(Wtx/Wt18)	-0.78824
Wt18/Wtx	1.633019 ESALs	Wt18/Wtx	6.14105 ESALs
When Lx is on a tandem or tridem (Lx/Ls)^4	1.576824 ESALs	When Lx is on a tandem or tridem (Lx/Ls)^4	4.983541 ESALs
Total Vehicle ESALs:	1.996203 ESALs	Total Vehicle ESALs:	6.504233 ESALs

<u>Flexible Pavement Model</u>: County Maintained Roads

Truck Example 1: Steering Axle	
Lx	13.881
L2	1
pt	2.5
SN	3.5
Gt	-0.20091
Bx	0.602262
B18	0.845334

Truck Description			
Class		7	
No. of Axles		4	
Gross Weight		67,669	
Axle Weights:	Axle 1	13,881	lbs
	Axle 2	12,559	lbs
	Axle 3	20696.2	lbs
	Axle 4	20532.7	lbs

Log(Wtx/Wt18)		0.412396	
Wt18/Wtx		0.386904	ESALs

When Lx is on a single axle

EALF	(Lx/18)^4	0.353666	ESALs

Assuming lift axle is raised

Truck Example 1: Tridem Axle	
Lx	53.788
L2	3
pt	2.5
SN	3.5
Gt	-0.20091
Bx	0.840004
B18	0.845334

Log(Wtx/Wt18)	-0.21323	
Wt18/Wtx	1.633912	ESALs

When Lx is on a tandem or tridem

(Lx/Ls)^4	1.576788	ESALs
Total Vehicle ESALs:	2.020817	ESALs

Assuming lift axle is deployed

Truck Example 1: Tandem Axle	
Lx	53.788
L2	2
pt	2.5
SN	3.5
Gt	-0.20091
Bx	1.939251
B18	0.845334

Log(Wtx/Wt18)	-0.80317	
Wt18/Wtx	6.355744	ESALs

When Lx is on a tandem or tridem

(Lx/Ls)^4	4.98343	ESALs
Total Vehicle ESALs:	6.742648	ESALs

Flexible Pavement Model: Municipal Maintained Roads

Truck Example 1: Steering Axle

Lx	13.881
L2	1
pt	2.5
SN	4.5
Gt	-0.20091
Bx	0.471385
B18	0.557173

Truck Description

Class	7		
No. of Axles	4		
Gross Weight	67,669		
Axle Weights:	Axle 1	13,881	lbs
	Axle 2	12,559	lbs
	Axle 3	20696.2	lbs
	Axle 4	20532.7	lbs

Log(Wtx/Wt18) 0.442696

Wt18/Wtx 0.360831 ESALs

When Lx is on a single axle

EALF (Lx/18)^4 0.353666 ESALs

Assuming lift axle is raised

Truck Example 1: Tridem Axle

Lx	53.788
L2	3
pt	2.5
SN	4.5
Gt	-0.20091
Bx	0.555294
B18	0.557173

Log(Wtx/Wt18) -0.21295

Wt18/Wtx 1.63286 ESALs

When Lx is on a tandem or tridem

(Lx/Ls)^4 1.576824 ESALs

Total Vehicle ESALs: 1.9937 ESALs

Assuming lift axle is deployed

Truck Example 1: Tandem Axle

Lx	53.788
L2	2
pt	2.5
SN	4.5
Gt	-0.20091
Bx	0.94326
B18	0.557173

Log(Wtx/Wt18) -0.78965

Wt18/Wtx 6.161006 ESALs

When Lx is on a tandem or tridem

(Lx/Ls)^4 4.983541 ESALs

Total Vehicle ESALs: 6.521837 ESALs

Rigid Pavement Model: All Networks

Truck Example 1: Steering Axle

Lx	13.881	
L2	1	
pt	2.5	
D	9	in
Gt	-0.17609	
Bx	1.014709	
B18	1.052411	

Truck Description

Class	7		
No. of Axles	4		
Gross Weight	67,669		
Axle Weights:	Axle 1	13,881	lbs
	Axle 2	12,559	lbs
	Axle 3	20696.2	lbs
	Axle 4	20532.7	lbs

Log(Wtx/Wt18) 0.484064

Wt18/Wtx 0.328047 ESALs

Assuming lift axle is raised

Truck Example 1: Tridem

Lx	53.788	
L2	3	
pt	2.5	
D	9	in
Gt	-0.17609	
Bx	1.325523	
B18	1.052411	

Log(Wtx/Wt18) -0.5974

Wt18/Wtx 3.957291 ESALs

Total Vehicle ESALs: 4.285338 ESALs

Assuming lift axle is deployed

Truck Example 1: Tridem

Lx	53.788	
L2	2	
pt	2.5	
D	9	in
Gt	-0.17609	
Bx	2.236805	
B18	1.052411	

Log(Wtx/Wt18) -1.08521

Wt18/Wtx 12.1677 ESALs

Total Vehicle ESALs: 12.49574 ESALs

Pavement Calculations

ESAL Calculations			
Axle Weights (tons)	**Single**	**Tandem**	**Tridem**
0	0	0	0
2	0.0024387	0.00015	4.82253E-05
4	0.0390184	0.00244	0.000771605
6	0.1975309	0.01235	0.00390625
8	0.6242951	0.03902	0.012345679
10	1.5241579	0.09526	0.030140818
12	3.1604938	0.19753	0.0625
14	5.855205	0.36595	0.115788966
16	9.9887212	0.6243	0.197530864
18	16	1	0.31640625
20	24.386526	1.52416	0.482253086
22	35.704313	2.23152	0.706066744
24	50.567901	3.16049	1
26	69.650358	4.35315	1.37736304
28	93.68328	5.8552	1.852623457
30	123.45679	7.71605	2.44140625

Pavement Condition Over Time						
Time	Delta	Pe		Time	Delta	Pe
1	0.017	4.128		18	0.017293	3.076555187
2	0.017	4.057		19	0.017293	3.023809697
3	0.017	3.988		20	0.017293	2.971968492
4	0.017	3.919		21	0.017293	2.921016071
5	0.017	3.852		22	0.017293	2.870937195
6	0.017	3.786		23	0.017293	2.821716888
7	0.017	3.721		24	0.017293	2.773340431
8	0.017	3.657		25	0.017293	2.725793355
9	0.017	3.595		26	0.017293	2.679061443
10	0.017	3.533		27	0.017293	2.633130718
11	0.017	3.472		28	0.017293	2.587987445
12	0.017	3.413		29	0.017293	2.543618123
13	0.017	3.354		30	0.017293	2.500009484
14	0.017	3.297		31	0.017293	2.457148485
15	0.017	3.24		32	0.017293	2.41502231
16	0.017	3.185		33	0.017293	2.373618361
17	0.017	3.13		34	0.017293	2.332924254

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