ABSTRACT

Title of Document: Examining the Impact to Highways and Structures by Vehicles Equipped With Lift Axles

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The rise in Lift Axle Trucks in Maryland Roadways has brought attention to truck policies and regulations. A lift axle is an additional axle located on the truck that has the ability to be raised or deployed based on the Gross Vehicle Weight or the weight of cargo carried by the truck. Lift axles allow the truck to carry substantially higher payloads or cargo for a small increase in vehicle cost. There is much concern in the lift axle operation (the rise and deployment) based on weight, it could have a significant effect on the condition of pavement and bridge structures. This research study examined the federal and state truck regulations as well as lift axle truck configurations. Furthermore, based on truck digital weight and size data, the study explored the behavior of pavement and highway bridges based on the rise and deployment of lift axle, punching shear, yield line analysis as well as girder analysis and pavement damage. Results show that high rear tandem axle weights will have a higher effect on pavement and bridges than compared to tridem rear axle truck configuration (single unit truck with axle down) due to the loads being more distributed.

EXAMINING THE EFFECT TO HIGHWAYS AND STRUCTURES BY VEHICLES EQUIPPED WITH LIFT AXLES

By

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Problem Statement

In today's highway network, there is an abundance of lift axle vehicles. The rise in this new innovative source of technology has been a large benefit to companies allowing them to increase Gross Vehicle Weight while still meeting the Federal Bridge Formula Law Regulations. While lift axles allow trucks to carry more weight and assist in distributing it equally, concerns still arise.

One concern is the increase in overweight vehicles. Vehicles with lift axles are being found (by enforcement) to be 20,000 to 30,000 lbs over the vehicle weight limits. Aside from overweight vehicles, the rise and deployment of the lift axle also presents some concern. If the driver raises the lift axle and neglects to deploy it at the appropriate time, this then adds more weight on the back tandem axles or rear axles. Essentially this may have the potential for a substantial amount of highway damage to both pavement and bridge structures.

Currently, in Maryland there are minimal regulations in reference to lift axle vehicles. Maryland regulations give specifications of down force pressure capacity when the lift axle is engaged with the pavement. Furthermore, there are no regulations on other lift axles that may possibly be attached to the vehicle (vehicles not classified as 4 axle dump service trucks). As long as the Gross Vehicle Weight (GVW) meets the Federal Bridge Formula (also known as Bridge Formula B) Law Regulations lift axle or fixed when weighed, there are no concerns with enforcement. But one enforcement concern presents itself in portable weights carried by roving crews. If the roving crews do not have proper number of portable scales to weigh a vehicle larger than a 4 axle dump truck then if the crew is not within 10 miles of a static weigh station, then Maryland law does not require enforcement to mandate the vehicle to drive to a weigh station.

Overall, there are not only concerns with potential damage to pavement and bridge structures, but also this presents concerns with policy and enforcement. This report took the time to examine the above concerns. It also laid out data collection and analysis that will assist in summarizes the concerns with lift axles.

1.2 Research Objectives & Scope of Work

In order to completely investigate the effects of lift axle trucks, the following research objectives have been outlined:

- Locate, assemble and document other states requirements and concerns for lift-axle 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
- If it is determined this is a significant problem, examine, identify, and recommend 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 the Maryland State Highway Administration. The report discusses Maryland policy as it compares to other states' lift axle policies. Survey results on a state, national, and international level as well as statistical analysis 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 axle on roads and bridges.

1.3 Research Approach

In approaching the research topic, the following four tasks outlined discuss research tactics to display results of the topic:

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

In this task, the issues were identified. In Maryland, state law only covers 4-axle dump service vehicles in lift axle regulations, but does not regulate any other vehicle equipped with lift axles nor does it address vehicles that may be equipped with multiple lift-axles. Maryland is also experiencing 4-axle dump service vehicles raising the lift-axle before going through toll booths which reduces the amount of 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 that shall determine whether the lift axle is raised or deployed. While these specifications are outlined for dump service vehicles, there are no specifications on any other type of vehicle.

The focus was to locate, collect and list all the available current state-of-the-practice methods for (1) Federal Highway Administration's (FHWA) regulations covering lift-axle 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. Published material on the subject areas was thoroughly searched through TRB, ASCE, Transportation Research Information Services (TRIS), National Technical Information Service (NTIS), Transportation Research Laboratory (TRRL) and other states. The research team also searched historical Maryland policies to evaluate the history of the dump service truck, lift axle regulations, as well as pavement and bridges across the state for damage due to material problems.

The literature review also addresses additional issues associated with lift-axle vehicles beyond laws and regulations, which are (1) lift-axle vehicle design and use, (2) highway safety consideration, (3) vehicle, pavement and bridge damage consideration, (4) economic consideration.

Task 2: *Survey Other States to Find Their Practice and Regulations on Lift-axle Vehicle*

Survey was conducted through AASHTO, Commercial Vehicle Safety Alliance (CVSA) and other channels to gather information on lift axle regulations. The survey examines basics as for as regulations covering lift-axle vehicles or implementation specifications vehicles registered in their state for in state registered and foreign vehicles. The survey covers (1) vehicle weight policies (2) state truck regulations (3) deterioration by trucks (4) and lift axle regulations. The survey discussed permit or approval requirements, weight specifications other than Federal Bridge Formula (FBF), equipment and truck specification. Also in the survey are identified issues relevant to Maryland current law of covering only 4-axle dump service vehicles. From the survey, information was gathered in reference to absence of lift axle regulations in other states and the research team was able to identify what states are doing to examine this problem and what methods are being employed to solve them which can be used in Maryland.

Task 3: *Identify Analytical Approaches to Measure Behavior of Roadways and Bridge Structures based on Usage of Lift Axle*

Data was collected from a Maryland Virtual Weigh Station on Local State Route 32. The Virtual Weigh station was able to capture 1 year of data including all classes and combinations of vehicles. The collected information included fully loaded vehicle operating with lift-axle not engaged, over gross vehicle weight limits, improper weight on lift-axle, and insufficient air-pressure for lift-axle. The theoretical approaches were then applied to the digital data from the Maryland Route 32 virtual weight station site. Appropriate statistical analysis was completed for the best display of results.

Task 4: *Conclusions and Recommendations*

Literature and survey results gathered from federal, states' and in-state levels has been summarized and analyzed. The summary addresses if 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. It also discusses the effect of these lift axle trucks on bridge structures and the health of Maryland Structures. The research team has organized, evaluated, and documented the information acquired and produce a final report assessing the project. This would include identifying advantages, disadvantages, areas of concern, etc. Conclusions and recommendations 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 the truck to carry substantially higher payloads or cargo for a small increase in vehicle cost. Lift axles can be raised or deployed based on the weight being carried. It is vital to understand the role of lift axles in the configuration of a truck. In order to thoroughly understand its role, various things should be considered, operational usage and why they are used. A lift axle is an additional axle (not fixed) located on the truck that has the ability to be raised or deployed based on the Gross Vehicle Weight or the weight of cargo carried by the truck. Most lift axles are operated by the usage of a hydraulic or air pressure bag technology in the axle configuration which delegates the loading and unloading of the lift axle. The increase in pressure on the lift signals the lift axle to be lowered and the lift axle will assist in the total distribution of the vehicles gross weight. Some of the drawbacks to the usage of Lift Axles are as follows (Sivakumar 2007):

- 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: 4-axle Dump Truck with Lift Axle (L) and 7-axle Truck with Lift Axles (Ref: maxleairride.com) (R)

There is also a variety in the control system of the lift axle. The lift axle can have a switch on the interior of the cab where the driver delegate when the lift axle is raised or down. This same switch could also be on the exterior of the cab. Raising and deployment can only be controlled from the exterior. And also another common notion is having the deployment switch on the interior and the regulating switch on the outside. This simply means that the driver controls when it is down but cannot control when it rises from the interior of the cab.

Steering also becomes another concern with lift axle trucks. Some axles are non steerable where steering around corners and on curves become difficult. The only way to ease maneuverability would be to raise the non steer axle when turning. But when lifting the axle to steer around corners or turns, this possible could create 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 road surface. This essentially creates less potential for pavement wear. Self steering axles usually come in an array of load capacities and specifications. Most lift axles operate with single tires but there are lift axles equipped with dual tires but are rare.(Koehne and Mahoney 1994).

2.2 Truck Policies

2.2.1 National Policies

On a national level, the American Association of State Highway and Transportation Officials (AASHTO) has done quite a few research on legal truck loads and their effects on the national highway systems. The Federal Bridge Formula Law (FBF B) is a law that limits loading 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 B is given as follows:

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

Where,

W= the maximum weight in pounds that can be carried on a group of two or more 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 put limits on vehicle weights operating on the Interstate System to protect the federal bridge structures. A maximum gross weight limit of 73,200 pounds along with 18,000 pounds on single axles and 32,000 pounds on tandem axles was established. Some states were allowed to maintain or “grandfather” their local truck weights.

With this regulations being adopted by Congress in 1975, this issue grew more and more controversial over the years and more states used their right to grandfather their existing rights. The maximum gross weight is 80,000 pounds.

More specifically, Lift axles are used on more than 70% of all four-axle single-unit trucks (Sidvakumar, 2007) which is also very popular in Maryland. AASHTO designed the following criteria for lift axle 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 9000 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 in load capacity with relevant State regulations or with Federal Motor Vehicle Safety (FMVS) standards or with both as is deemed appropriate.

A national survey was also completed asking states about their local policies as it pertains to state axle weight limits. The results can be found in appendix A. The survey also addresses hauling exemptions and permits pertaining along with weight tolerances for possible overweight axles (appendix A). The survey results showed the axle weight limits for single tandem, tridem and quadrum axle configurations. The survey also included question 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)

From national results of the report (NCHRP Report 575, 2007), there is a large variety in state regulations for lift axles for weighing protocol and especially monitoring weight and compliance. The report also examined state postings of loads with FBF formula. 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 kips. Federal law states that any two or more consecutive axles may not exceed the weight computed by the bridge formula.

2.2.2 International Policies

On an international level, Canada has a lot of experience in lift axle trucks on their roadways. Canadian Truck policies are indeed different with higher GVWs and allowance of 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 (30864.4 pounds)
- For a four axle vehicle, 25,000 kilograms (55115 pounds)

For 3 axle vehicles there are special provisions outlined in the table below.

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 is extremely familiar with lift axle technology, various provinces have created laws, policies and initiatives to regulate lift axle usage. Lift axles are not just popular on dump service trucks but 5- and 6-axle vehicles as well, there for the lift axle regulations do not just apply for dump service vehicles or commercial motor vehicles.

In Ontario, The following are a few 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 that the lift axle is raised and deployed based on the weight applied and any other conditions. Because of the quick rise in the usage of lift axles, Ontario has put together a new initiative called the Safe, Productive, Infrastructure-Friendly (SPIF) vehicles. This initiative was created to be as productive as possible while ensuring vehicle performance characteristics meet or exceed national guidelines and that heavy truck damage to roads and bridges is minimized. In this initiative, regulations have been modified and truck configurations and criteria have been outlined to get vehicles SPIF-ready and integrate new policies to existing vehicles on Ontario roads. SPIF vehicle regulations ensure safe manoeuvres of multi-axle vehicles and must be equipped with self-steering axles and load-equalization tools. The Ministry of Transportation 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 product being carried.

2.3 Structural Capacities based on Failure Modes

As mentioned in the previous section, All the national policy and state regulations are based on the Federal Bridge Formula Law (FBF B) where FBF B is a law that limits loading for overall protection of the highways and bridge structures, The guideline followed by the developers of FBF B was that a typical HS20-rated bridge would not be overstressed by more than 5 percent by the typical combination truck with one trailer. The concept of a bridge formula evolved a half a century ago, and it went through several revisions. The analyses conducted in developing Bridge Formula B considered only simply supported superstructures, but it is considered representative and the resulting formula was generally applicable to all cases. So, it can be stated that the policy was based on the capacities of the bridges. In this section, more are discussed with structural capacity study extended to pavements and bridge decks.

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

2.3.1 Punching Shear Approach

To examine the potential failure of the bridge structure it is safe to investigate the bridge deck. 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 deV Batchelor (1975) proposes 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 model proposes the analogy of comparing 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 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) on a *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 large deficiency in the code's consideration for the column-slab assembly relationship. The following calculation of punching shear is proposed:

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

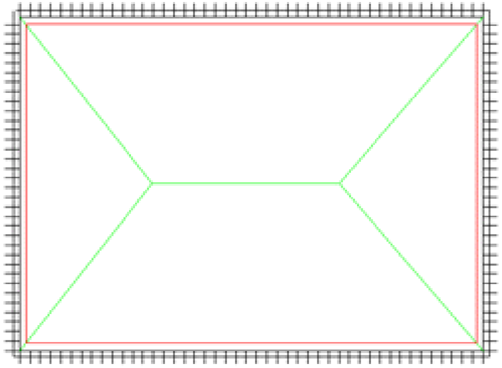
where V_{flex} is the product of the slab area tributary to the column and design load.

Among the approaches discussed above, the most rational approach for calculating the punching shear strength of bridge deck is the ACI 318-08 code formula which takes into account the dimensions of the load that is 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 in the by the American Concrete Institute is most efficient.

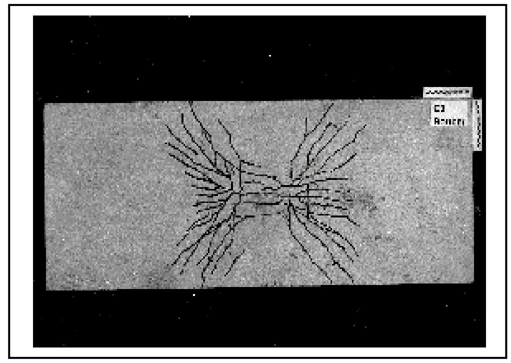
2.3.2 Yield Line Approach

Yield line theory is used to predict ultimate loads on a slab by postulating failure mechanism which is based on set boundary conditions. The yield line approach will be analyzed based on uniform reinforcement or an isotropic deck. 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 2.2: Yield Line Pattern from Uniformly Loaded Simply Supported Slab

Park and Gamble (2000) suggest that there are two means 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. Work will be done by external 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 distributions and magnitudes of the shear does not need to be known in formulating the calculations along the yield line but in the equilibrium approach all action need to be known in order to complete the calculation. In this case, yield line theory has been applied to concrete deck with external loads exuded from truck axle loads.

However, Quintas (2003) suggests that the application of yield line theory is quiet 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 deck.

2.3.3: 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 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 factor in the design.

The analysis in this report is focused on bending moment. In bridge design, the bending moment stresses caused by the live, dead and dynamic loads, will also accommodate the fatigue and shear stresses. If the bending stress is in excess, the other stresses usually are excessive as well showing direct correlation between bending, shear and fatigue. Essentially, bending moment analysis assist in ensuring the strength and safety of the structure. Overall, little is gained by considering fatigue or other stresses, since the bending stress is a reasonable proxy for all stresses.

2.3.4 Potential Pavement Damage Approach

Various approaches are taken to estimate the potential pavement damage. In this report, it will discuss the Equivalent Single Axle Load (ESAL) Design approach to measure pavement damage on Maryland Local roads and highways to provide statistical support to examining the effects of Lift Axle Trucks. This approach was chosen as the best approach after reviewing an earlier report written by the Maryland State Highway Administration (1993) that investigated the effects of 3-axle and 4-axle Dump trucks in *The Impact of Dump Service Tag Vehicles on Maryland's Roads and Bridges*. The ESALs approach was used to measure damage and further more used the approach to connect damage costs to axle load damage to the pavement on both rural roads and highways. *AASHTO guide for design of pavement structures* (1993) outlines the design process for ESALs. The ESAL approach allows conversion of mixed vehicular traffic into its equivalent single-axle, 18-Kip Load. From this conversion, the relative damage per axle is calculated.

In the Equivalent Single Load approach, load applied to the tire, pavement thickness, and spacing between tires are considered in the design approach and does not consider any traffic information.(Y. Huang, 2004) Using the ESAL approach would allow isolation of the analysis of the lift axle. While many researchers use ESALs as the basis of their research, many use finite element approaches or road tests measuring strain, fatigue or rutting from the pavement to carefully examine the behavior of the pavement. The AASHTO ESALs method is very simple and compares very well to actual load tests using strain gage and earth pressure measurements for damage. (Lin, Wu, Huang, Juang, 1996). The ESAL approach uses single standard axle of 18 kips to compare with the actual vehicle axle loading. It also considers other factors such as structural design elements (for both rigid and flexible pavement), Annual Daily traffic, Annual Daily Truck Traffic, Lane Distributions and 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 Weigh in Motion (WIM) Data provided by MDSHA, the ESALs approach can be used to investigate various truck axle loading configurations.

The ESALs approach is another method to determining not only the effects of each axle load but loading contributions to the overall serviceability of the pavement structure. Below shows a figure that explains the pavement performance concept.

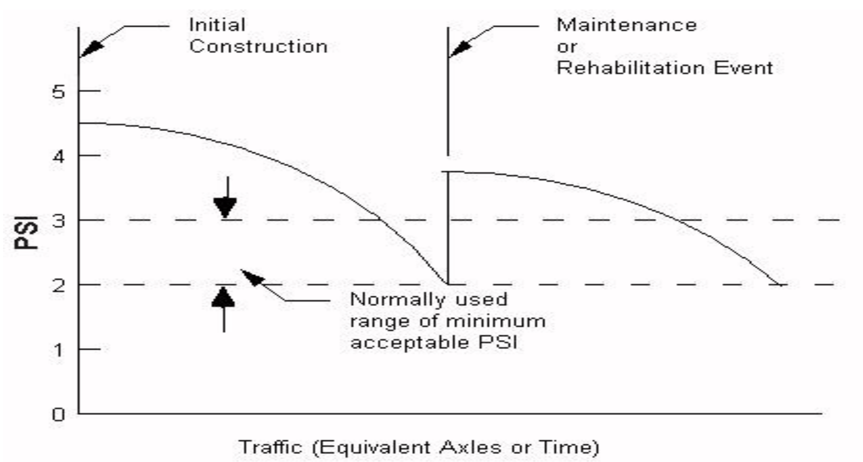


Figure 2.3: Concept of Pavement Performance Using
Present Serviceability Index (PSI) (Hveem and Carmany, 1948)

The figure displays Traffic in axles and time 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 Laods increase, the serviceability also heavily decreases as well.

Chapter 3: Policy Research

3.1 Maryland Truck Size and Weight Regulations

In the state of Maryland, truck policies correlate with those provided by the Federal Highway Administration. On Maryland interstates and state routes, the Federal Bridge Formula Law mandates all design criteria for gross and axle weights. The Federal Bridge formula law was created under the Federal Aid Highway Amendments of 1974 to limit axle weights and gross weights. Some states were allowed to utilize their grandfather rights to maintain truck weight and size requirements post implementation of the Federal Bridge Formula Law. After this enactment and due to increase of hauling and dump trucks on their state roads and interstates, Maryland needed to change their truck weight regulations. In 1991, The United States Congress made provisions to the Intermodal Surface Transportation Efficiency Act (ISTEA) that allowed Maryland to operate 70,000 pound 4-axle dump service vehicles in Alleghany and Garret Counties. And as early as 1993, Maryland General Assembly enacted law allowing statewide operation of these dump service vehicles. (MDSHA, 1993) Moreover, Dump Service Trucks became the great exception to Federal Regulations on roads and bridges in Maryland. So not only does Maryland comply with FBF B regulations but the State regulations as well set the standard for Maryland Dump trucks.

This new provision introduced a new wave of approach to Maryland Roads and dump trucks. Maryland began to not only discuss dump truck gross vehicle weights but number of axles and loading also became very important factor in the safety of Maryland highways and bridges. Dump Truck regulations are ever changing and evolving topic in the state of Maryland.

3.1.1 Dump Service Registered Trucks

Dump Service Registered Trucks are one of the more prominent truck types that receive much attention in the state of Maryland. In 1993, the Maryland General Assembly 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 most typical in hauling loose materials and used due to its mechanical means of self unloading. The gross weight limitations (TR 13-919) for a Dump Service truck are as follows:

- 40,000 pounds for 2 axle truck
- 55,000 pounds for 3 axle truck (prior to June1, 1994)
- 65,000 pounds for 4 axle truck (for vehicles registered prior to June 1, 1994)
- 70,000 pounds for 4 or more axles

In the effort to make transition to 4 axle dump trucks with a loaded at 70,000 from 3-axle at 65,000 pounds, the Maryland State General Assembly allowed dump trucks already registered as DSVs to continue to operate at 65,000 during the phase out period for owners with current 3 axle trucks. Legislation set a 20 year contingency period for the phase out process of Maryland “T-3” trucks until May 31, 2014 (COMAR11.15.27).

Dump Trucks that are hauling loose materials for more than 40 miles on non-highway routes (less than 2 lane divided roadways) must meet the proper gross weight limits (less than 2 lane divided roadways). Dump Service Trucks must not operate at more than a speed of 45 miles per hour. There are also a few exceptions for Alleghany and Garrett Counties due to higher frequency of dump trucks traveling on those country routes where (1) standard GVW for Dump Service Trucks is 70,000 pounds, (2) Dump Service Vehicles (DSV) are not subject to any

Maryland Vehicle restrictions such as gross weight or axle loads of a vehicle other than the restrictions on gross vehicle weight provided by the Dump Service Vehicle Requirements, (3) Dump Service Vehicles are not subject to any other restrictions of the Maryland Vehicle Law on the weight, gross weight, or axle loads unless 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).

The state of Maryland and bordering state, Delaware also have reciprocity regulations for those trucks that correlate with the specified characteristics of a dump service vehicle. The regulation was put into place in January 1996 to accommodate for the Dump Service Vehicle traffic not only for Maryland but for Delaware. It was enacted to also standardize regulations across borders with neighboring states.

3.2 National Survey Results

3.2.1 Lift Axle Survey

A 25-question survey was administered by the University of Maryland Bridge Engineering Software and Technology (BEST) Center to all 50 states' Department of Transportations' 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 states DOTs as well as 1 survey from the British Columbia (Canada). Also, there were 2 non survey responses from New Jersey as well as Saskatchewan (Canada). Below shows the spread of states in which surveys were received.

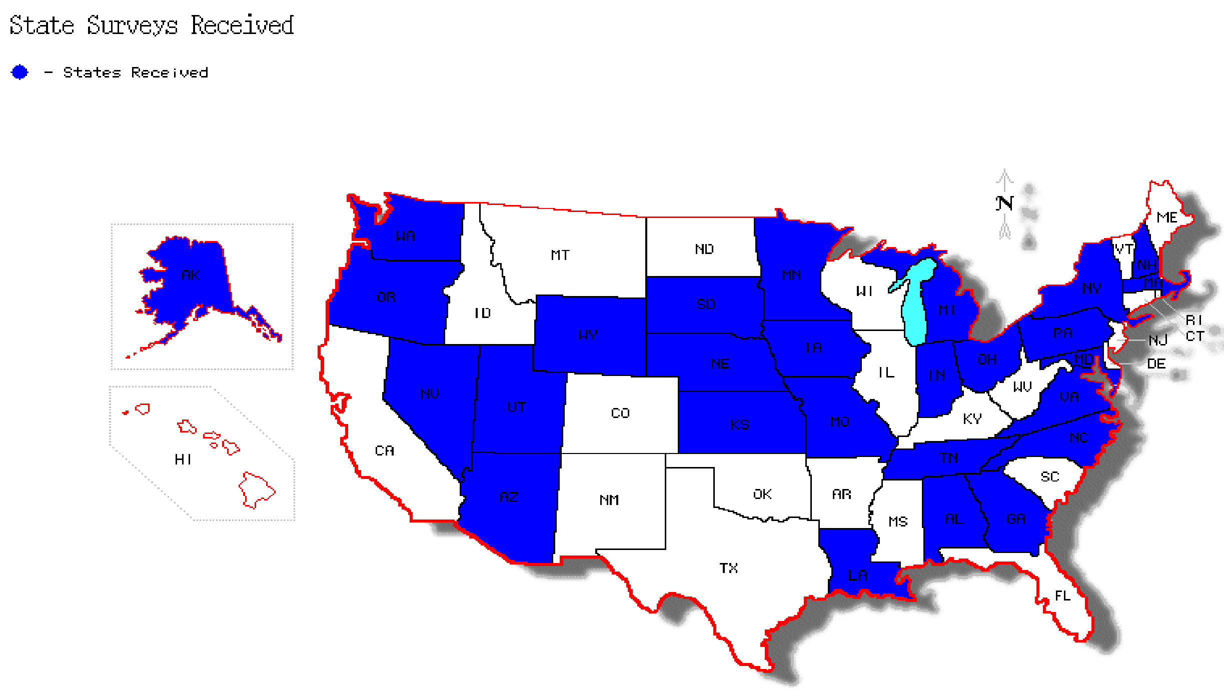


Figure 3.1: Map of State Survey Responses

The survey results do not include responses from the larger water bordering states such as Texas, California, as well as Florida which could alter results considering all 3 states have major import/export businesses. The state of New Jersey commented that there was not enough information to answer the survey thoroughly while Saskatchewan discussed their lift axle policies and compared it to some of the other Canadian Provinces.

3.2.1.1 Survey Section 1: Vehicle Weight Policies

In the section, the survey discusses vehicle weight policies as they pertain to those regulations set by FHWA. It discusses the notion of "grandfathered laws" where states were able to sustain their existing laws after the creation and enactment of new laws. This becomes especially important in weight policies because states use their grandfather rights to maintain Gross Vehicle Weights that are above the 80,000 pound maximum limit. Figure 3.2 shows the states responses for "grandfathered laws."

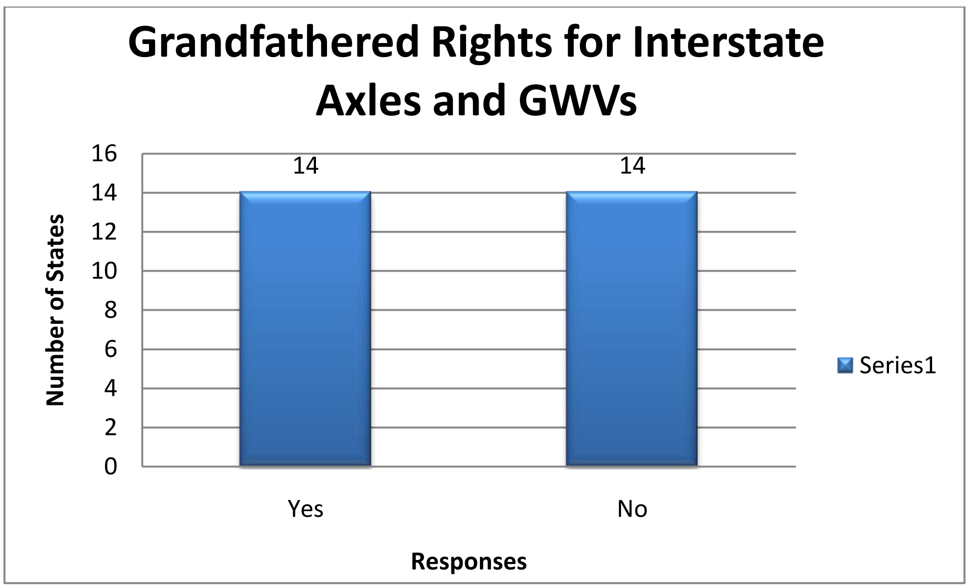
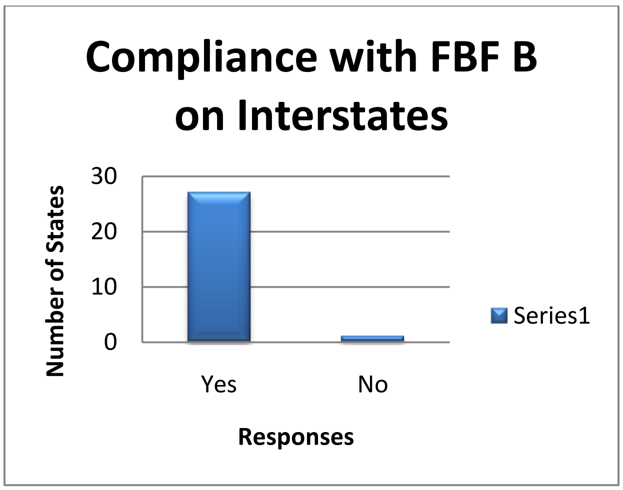


Figure 3.2: Graph of Survey Response for Question 1
Q1: Does your state currently utilize its grandfathered rights for Interstate axle and gross weight limits?

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

Furthermore, Maryland Dump Service Vehicles are the exception to the usage of the Federal Bridge Formula Law (FBF B) on Interstates and local routes. But Maryland State provisions read 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.” The figures below show States compliance with the FBF B Law on both interstates and local highways.



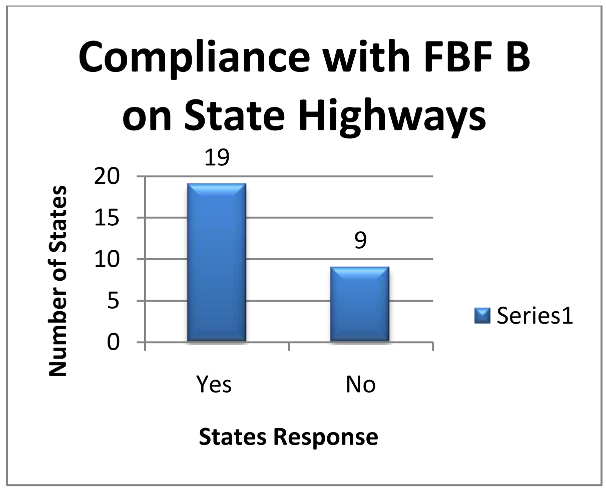


Figure 3.3(L) & Figure 3.4 (R): Survey Responses for State Compliance with FBF B Law on Interstates and Local Roads

In the figures above, it is evident that more states work to comply with Federal Regulations on the Interstates and seem less lenient on State and Local Routes. With 27 states complying with FBF B on Interstates, Maryland included in the “YES” response but the exception to the compliance is through the Dump Service Truck Regulation. On Local and State Highways, 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 become a concern as well on roadways and potentially could contribute to roadway deterioration as well as bridge fatigue and cracking. On an annual basis, States were asked to evaluate how many overweight trucks travelled on their roads.

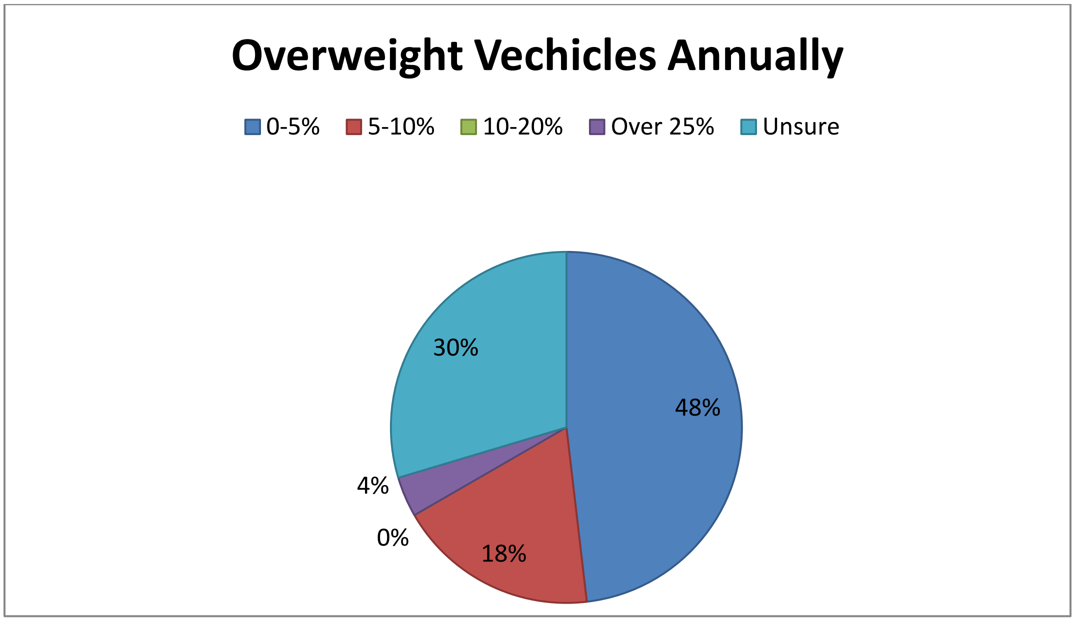


Figure 3.5: Survey Responses for Annual Percent (%) of Overweight Vehicles
Q7: What ratio best describes the number of overweight trucks annually statewide?

Figure 3.5 shows that almost half of the states evaluated their states as having 0-5% overweight trucks on their roads annually, Maryland included. While 30% of states were unsure did not have the information to be able to provide an answer. 18% of states chose 5-10% as the ration that best describes the amount of overweight trucks annually traveling on their roads while 4% of states expressed over 25% of their trucks were overweight annually.

The survey also discussed weigh station records, computer software as well as enforcement. 11 states review their weigh station records on a monthly basis while the next highest at 6 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, MSCEnforcement, 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.

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

The State Truck Regulation Section asked states to identify their state truck regulations in comparison to Federal Truck Regulations, especially as they pertain to weight limits. Twenty two states surveyed have their own state truck regulations. Of the 22 states that have truck regulations, 9 of those states gross vehicle weights exceed Federal GVW standards of 80,000 pounds ranging up to 129,000 pounds. Only 6 states have state axle suspension requirements including Maryland where there specifications simply require that suspension 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 are unsure about how much trucks contribute to pavement and roadways. Twenty states are unaware how much overweight trucks contribute to damage to bridge structures. This overall shows that most states either do not have a way of measuring how much damage trucks contribute to deterioration of roads and bridges or some states simply have implemented a means to measure this.

3.2.1.3 Maryland Lift Axle Regulation

The state of Maryland has seen an increase in the use of lift axle trucks more specifically with Dump Service Vehicles. Maryland currently has outlined regulations for lift axle vehicles. In order to meet Maryland lift axle 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). Other lift axle requirements are as follows:

- 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 can only be disengaged when in turning at an intersection at sharp curves (15 mph). The lift axle must also be raised when entering and exiting the delivery locations. The lift axle must also be raised when unloading cargo and can be disengaged for .25 miles before and after authorized raising during operation (COMAR 11.15.27.07).

As seen in section 3.1.2, Maryland does not make mention of the role of lift axles in the axle configuration for any of the above Dump Service Vehicles truck configurations. In the DSV requirements it touches on 4-axle trucks but most Dump Service Trucks are 4-axle dump trucks with 1 of the 4 axles being a lift axle. There is no mention in either Dump Service Vehicle Regulations or the Lift Axle regulation that mentions enforcement means or details on weighing trucks with lift axles.

Likewise, 12 states have lift axle regulations where in Georgia Lift Axle Trucks are banned. The figure below shows the Survey Responses for Lift Axle Regulations.

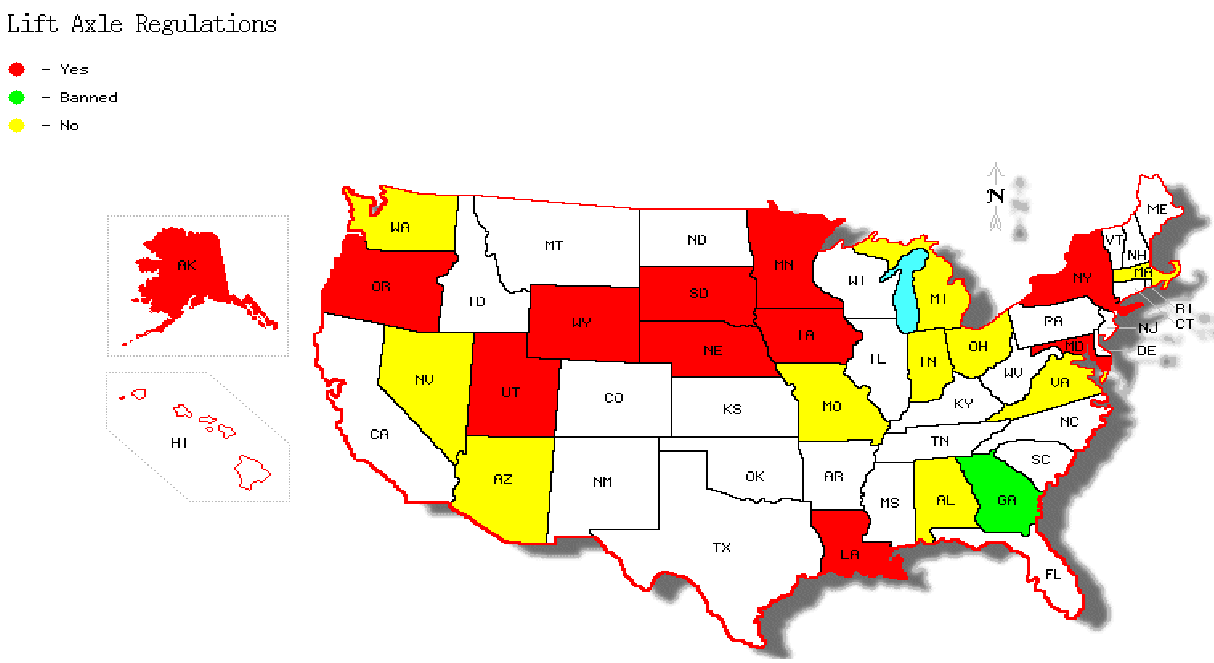


Figure 3.6: Lift Axle Regulation Survey Responses Question 14
Q14: Does your state have specific lift axle regulations?

The survey also asks states to examine specifications of their lift axle configuration. This serves as a means for states to truly look at equipment on the trucks that are on their roads. Often times lift axles are deployed when they should be raised and this could be from simple neglect to raise axle on account of the driver or malfunctioning of automatic control system. The figure below shows that of the states surveyed about 1/3 states have specifications that fall in each category.

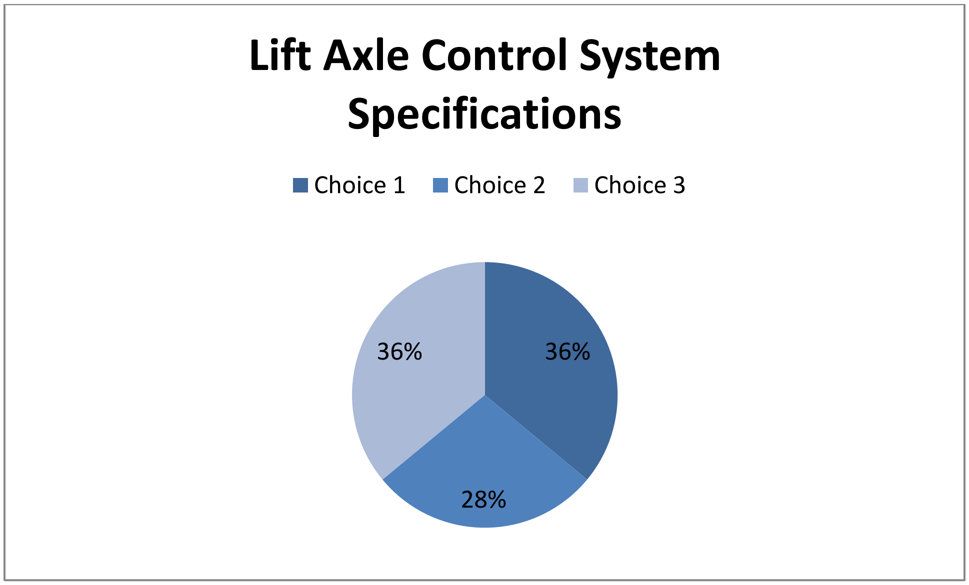


Figure 3.7: Survey Responses for Lift Axle Control System Specifications

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, we also asked states about suspension requirements, lift axle configurations, and equipment. Eight states use Federal fixed axle regulations for lift axles while 11 states have specific lift axle configurations for operation. Eight states also have lift axle steering or equipment specifications. Compared to Maryland, the specifications just need to be in safe operating conditions but no major specifications other than the position of the control system. Moreover, five states have specific lift axle configuration specifications. In addition, the survey also asked states to evaluate the amount of overweight trucks with lift axles annually and 17 states were unsure while 17 states claimed dump trucks were the most popular for lift-axle truck types.

3.3 Canadian Survey Results

As mentioned in Chapter 2, Canada has much experience in lift axle technology. There are distinct differences among the various regulations in each province. The British Columbia submitted a survey as well answering based on their policies. The maximum gross vehicle weight combination is 140,000 pounds oppose to the United States' 80,000 pounds. The survey explained that lift axles are banned in the British Columbia yet there are exceptions where they are permitted. 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).

The British Columbia also has 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.

Although Saskatchewan only submitted a small comment, their lift axle regulations were discussed. Lift axles are also prohibited in their province. Like the 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 is only lifted from the road surface when the vehicle is empty. Therefore, with the axle lifted it decreases operating costs and component wear on pavement. Lift axle systems are only allowed on semi-trailers and full trailers.

Chapter 4: Theoretical Approach

4.1 Statistical Analysis Assumptions

Weigh in Motion data from MD State Route 32 has been collected for this report analysis. Because of the abundance of data, data has been broken down into months. With 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.

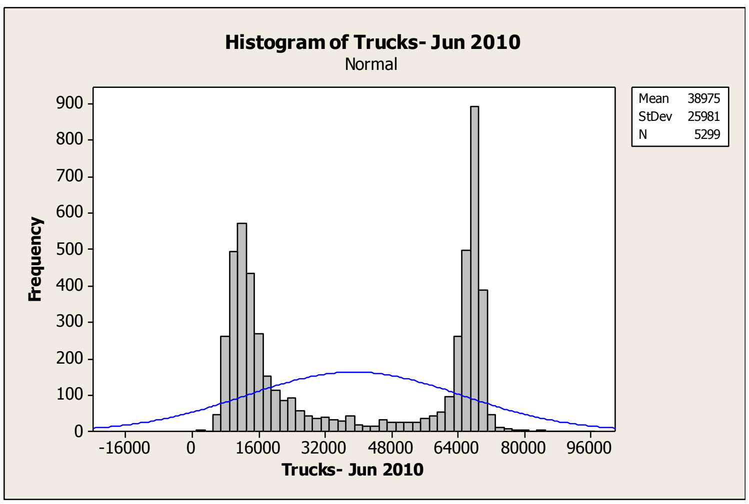


Figure 4.1: Distribution of Total Trucks for June 2010 from Virtual Weigh Station

It is found that there are two distributions present in the data which assists in specifying the bounds of the data. The new lower bound of the data becomes 50,000 lbs (gross weight) up to the highest 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:

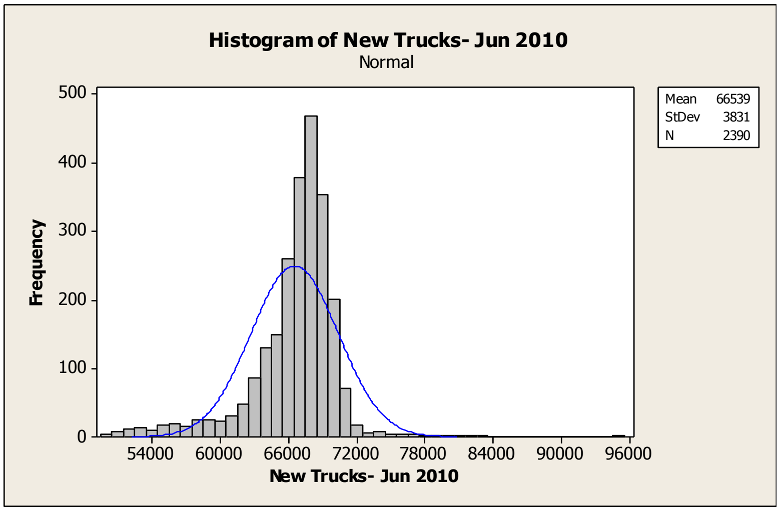


Figure 4.2: Distribution of Trucks with New Bounds

After reviewing this distribution, a new range is defined as 65,000-70,000 lbs which includes 1,645 trucks which is approximately 68.8% of the 2,390 trucks over 50,000 lbs.

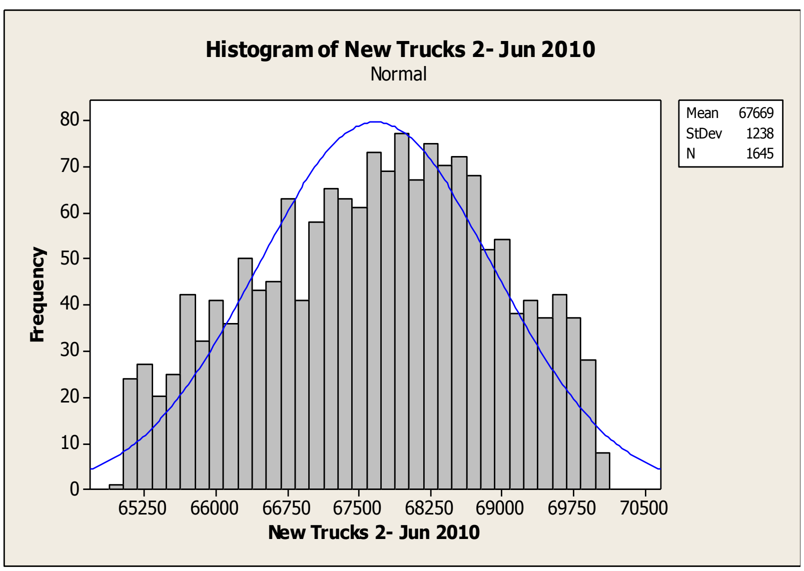


Figure. 4.3 Distribution of Trucks with New Bounds 65,000 to 70,000 lb

The mean gross weight is 67,669 lbs with a standard deviation of 1238 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: 67669.2 lb
    - Average Axle Weights:
        - Axle 1: 13881 lb
        - Axle 2: 12559.3 lb (Lift Axle)
        - Axle 3: 20696.2 lb
        - Axle 4: 20532.7 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 shows the distribution of the lift axle.

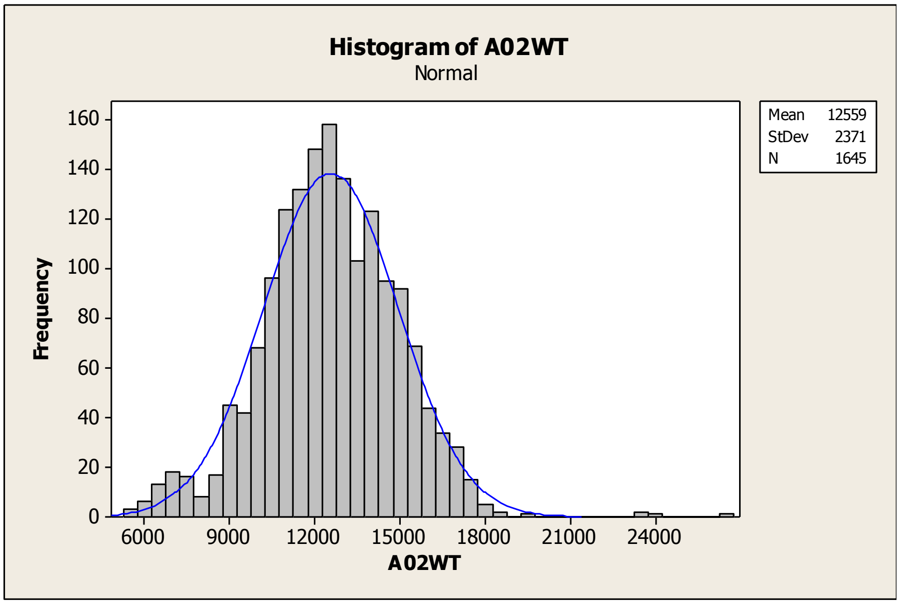


Figure 4.4: Distribution of Lift Axle Weights for the 65,000 to 70,000 lb Range

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.

4.2: Punching Shear Approach for Bridge decks

Based on the study of different approaches for punching shear, the approach proposed by the ACI code has been selected. The ACI code approach takes into consideration the perimeter of the punching shear region and the area of influence which is depended on the configuration of the load that is acting which is accounted by the factor β.

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

$$V_c = \left(1 + \frac{2}{\beta}\right) * (f_c{}')^{\frac{1}{2}} * b_0 * \frac{d_{av}}{6} \quad (4\text{-}1)$$

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 kips. 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 4.1.

4.3: Yield Line Theory for Bridge Decks

Quintas (2003) proposed two methods of determining yield lines patterns combine 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. But Quintas proposed the two methods to be able to gain the “correct” results.

The calculation of bending and twisting moments acting at 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 moments and twists 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 4.5 for Simple Supported Slab example with notations)

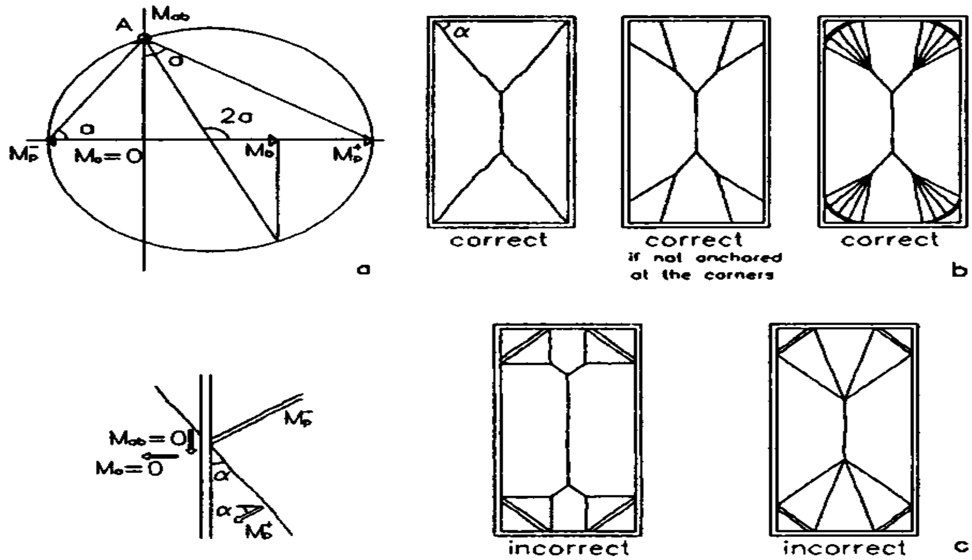


Figure 4.5: Examples of Yield lines Notation (Quintas, 2003)

The tandem and tridem loading configurations (truck from 4.1) 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 involved in a typical slab in yield line analysis. Thus only the 2^{nd}, 3^{rd}, 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 4.6). The longitudinal length l_y is a function of the girder spacing and the angle of failure

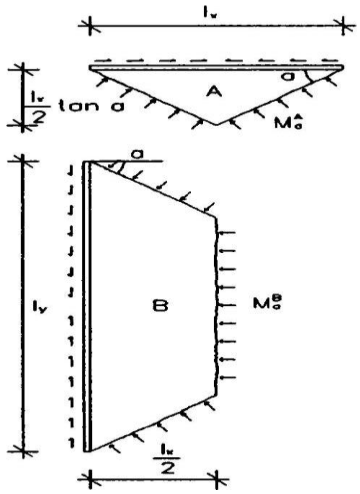


Figure 4.6: Moment Regions of a simply supported slab (Quintas, 2003)

The following formulas were used to calculate the bending moments and in turn determine yield line theory.

$$M_x^A = \frac{p{l_x}^2}{24}\tan(\mathrm{a})^2 \quad (4\text{-}2)$$

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

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.

4.4: Girder Analysis for Bridge Girders

There are various loading that effects the behavior of the bridge structure. Bending Moment is the most popular approach in the analysis of bridge girders. In this approach, the bending moment is calculated based on the truck loading and spacing configurations. Then by using the influence line fundamentals, the maximum 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. In this case, 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 varies 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 trucks configuration 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 their respective points, more specifically the midpoint for the maximum moment. The moment distribution factor for the live load is calculated based on span length as:

$$D_m = 0.075 + \left(\frac{S}{9.5}\right)^{0.6} \left(\frac{S}{L}\right)^{0.2}, \tag{4-4}$$

where S is the girder spacing and L is span length

For design moments and shear, the impact factor is assumed to 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 neglected from the calculation.

4.5: Potential Pavement Damage

The effects of lift axle 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

More specifically, in this report, multiple axle heavy loaded vehicles is investigated. In pavement design, AASHTO has developed a method called the Equivalent Single Axle Load (ESAL) concept in order to measure effects of axle loads on pavement. Essentially, the ESAL concept calculates the relative damage to a pavement structure due to different axle loading. It defines the damage per pass to a pavement as it relates to the damage per pass of a standard axle load which is 18-kip single axle load. The method looks at the total number of passes of the standard axle load during a given period and is computed:

$$\log\left(\frac{W_{t18}}{W_{tx}}\right) = 4.79\log(18+1) - 4.79\log(L_x + L_2) + 4.33\log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \tag{4-5}$$

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 kip axle load

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

$G_t = \log\left(\frac{4.2-p_t}{4.2-1.5}\right)$, where p_t is the ratio of lost in serviceability. (4-6)

$\beta = 0.4 + (\frac{0.081(L_x + L_2)^{3.23}}{(SN+1)^{5.19}\, L_2^{3.23}})$, (4-7)

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

For Rigid Pavement,

$\log\left(\frac{W_{t18}}{W_{tx}}\right) = 4.62\log(18+1) - 4.62\log(L_x + L_2) + 3.28\log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}}$, (4-8)

$G_t = \log\left(\frac{4.5-p_t}{4.5-1.5}\right)$ where p_t is the ration in lost in serviceability. (4-9)

$\beta = 1.0 + (\frac{3.63(L_x + L_2)^{5.20}}{(D+1)^{8.46}\, L_2^{3.52}})$where D is the thickness of slab, (4-10)

which yields the Equivalent Axle Load Factor(EALF). The EALF that will be later used to calculate the ESAL. It is assumed that the fourth power rule can be used in verification of the calculation of the EALF. 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, (4-11)
- $EALF = (\frac{L_x}{L_s})^4$, where L_s is the load in kips on the standard axles which have the same number of axles as L_s. (4-12)

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

$$ESAL = (ADT)(T)(T_f)(G)(D)(L)(365)(Y) \quad (4\text{-}13)$$

where the ADT is the Annual Daily Traffic on the specified roadway. The ADTT is the Annual Daily Truck Traffic or in this case the T is the Annual Daily Truck Traffic which is a percentage of the ADT. The Truck factor takes the sum of ESALs weighed for all trucks weighed divided by the number of trucks weighed. The Growth factor 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 distribute traffic by number of lanes (L) to make a more accurate prediction for pavement and Y is the year. All of these factors contribute to the ESALs calculation. 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 (4 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 substitutes as the final ESAL calculation. After examining the nominal truck case based on statistical data, conclusions are made 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 relationship, it is modeled as follows:

$$\delta = -\frac{\ln\left(\frac{P_T}{P_I}\right)}{L}, \quad (4\text{-}14)$$

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:

$$P_E = P_I e^{(-t\delta)} \quad (4\text{-}15)$$

where t= is the number of years.

Chapter 5: Data Analysis

5.1 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 5.1) and tandem (with lift axle load equally shared by two rear axles) cases.

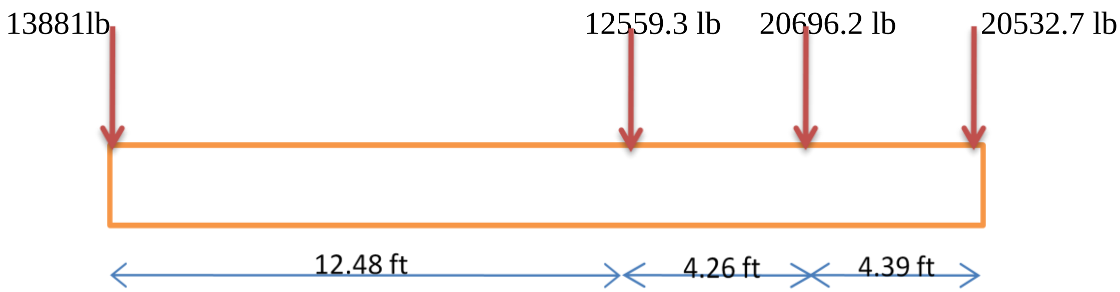


Figure 5.1: Truck Axle Loading Configuration

The following tables summarize the punching shear capacity for 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 in (kips)	28.08	32.32	36.62	40.97	45.38	49.85

Table 5.1: 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
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
b_0	170	172	174	176	178	180
V (kips)	21.19	24.51	27.89	31.35	34.87	38.47

Table 5.2: Punching Shear Capacity for Tandem Axle Rear Axle Configuration

The next table summarizes the punching shear capacity ratio of the comparison of tridem axle configuration versus the tandem axle:

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

Table 5.3: Tridem Axle to Tandem Rear Axle Ratio

It is found that as the depth of the slab increases the ratio slowly decreases but the change is very small between slab depths of 7 inches to 11 inches.

The next table considers the difference between 3-axle whole block and 2-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 5.4: 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. However the punching shear capacity ratio of 3-axle to 2-axle rear axles remain constant at about 1.32. But as the gradual addition of loading on the lift axle, the ratio load carrying capacity varies from 1.06 to 1.32 at 100% (lift axle deployed and in contact with pavement). Overall, the percent difference between the tandem axle and tridem axle is 32.549 % .

5.2 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. The following tables summarize the analysis.

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

Table 5.5: Tridem Axle Computations for Bending Moments

For tandem loading,

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

Table 5.6: Tandem Axle Computations for Bending Moments

Moment Ratio Tandem axle to Tridem axle

Girder Spacing(ft)	$\mathbf{M^A_x}$	$\mathbf{M^B_x}$
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: 5.7: Summary of Tandem to Tridem Axle Moment Ratios for Girder Spacing 7-11 ft

From the summary tables, it is evident that the ratio of the moment resistance capacity of the slab is remaining constant with the change in the slab configuration. 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 significant higher compared to those generated on tridem, approximately two times higher. This can be due to higher axle loads on the tandem rear axle thus causing a peak in the bending moment diagram at those higher loads, hence resulting into greater moments for tandem cases

5.3 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. Below are the results from the bending moment calculations.

S.L.	**Max LL Moment, For LRFD for Tandem Axle**	**Max LL Moment, For LRFD for Tridem Axle**	**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 5.8: Bending Moment Summary for Tandem and Tridem Axle Configuration

The bending moments for the tandem axle case at 10 feet to 20 feet had the higher percent difference compared to the tridem axle case. As the span lengths increase the percent difference remained from 0.06% to 0.01%. The following shows these values graphically.

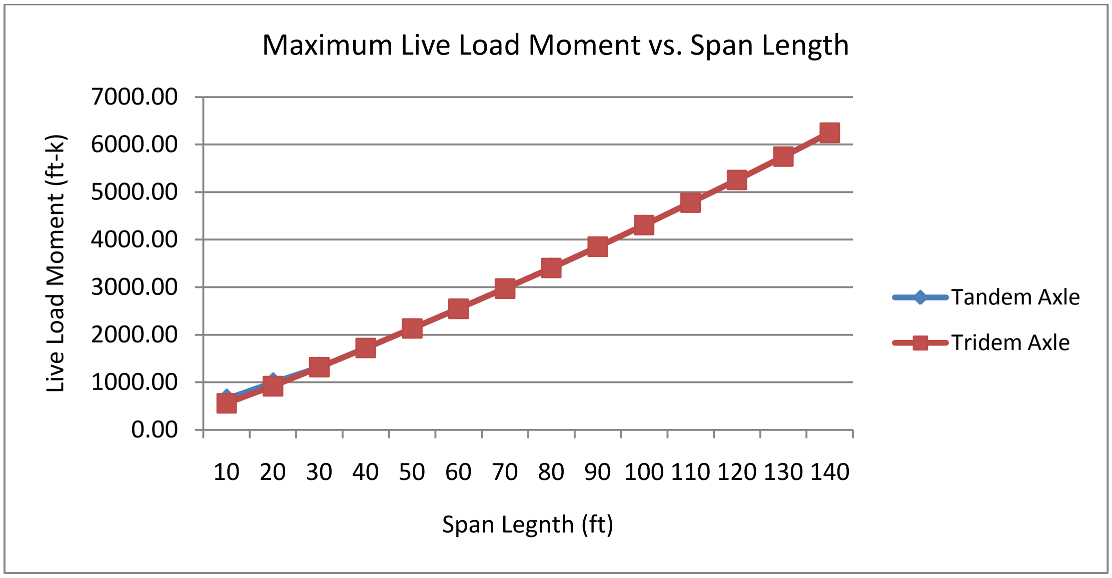


Figure 5.2: Maximum Live Load Moment of the Tandem and Tridem Axle Configurations

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 shorter 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 3 rear axles. For those shorter span bridges under 20 feet, since they are not included in the National Bridge Inventory, overall the tandem and tridem axle bending moments on the bridge has very little difference. So in the case of most highway bridges, the lift axle raise or deployed does not have much effect on the bridge girders if it is a medium or long span bridge structure.

5.4 Pavement Analysis Results

There are two major types of pavements: flexible or asphalt pavements, rigid or concrete pavements that were considered. Flexible pavements include the conventional types of layered systems that have higher strength materials near the top where the stresses are high. Rigid pavements 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)

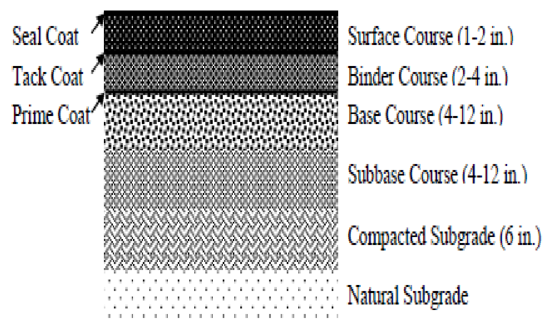


Figure 5.3: Typical Cross Section of Conventional Flexible Pavement (Huang, 2004)

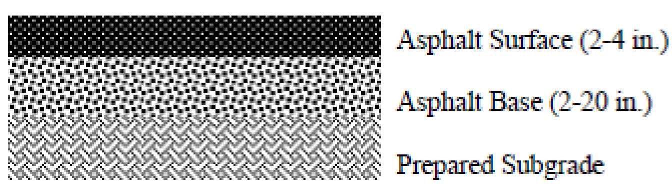


Figure 5.4: Typical Cross Section of Asphalt Pavement (Huang, 2004)

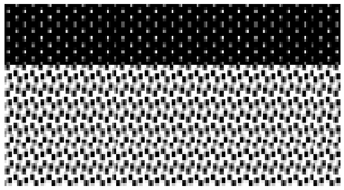


Figure 5.5: Typical Cross Section for Rigid Pavement (Huang, 2004)

The Equivalent Single Axle Load (ESAL) was used to measure potential damage completed by the nominal truck. 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 has not dramatically changed currently. 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 9 in which is typical for pavement. The ESAL calculation was applied 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. The tables 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 5.9: 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 5.10: 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. 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 3-axle truck creates about 3 times more damage than a 4-axle truck with a lift axle with equal gross weights. This displays 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 neglected or 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 potentially could create more road damage. The following figure shows the ESAL values for 3 axle combinations that show the damage increases as the weight increases. It is again illustrated that there is less damage when the load is distributed among more axles.

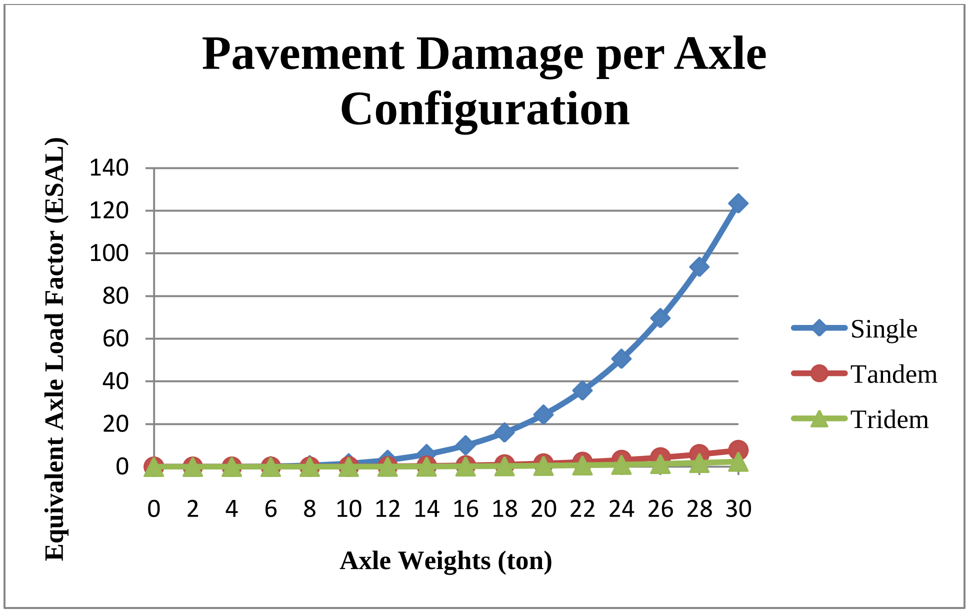


Figure 5.6: Pavement Damage Calculations for Single Tandem and Tridem Axles

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

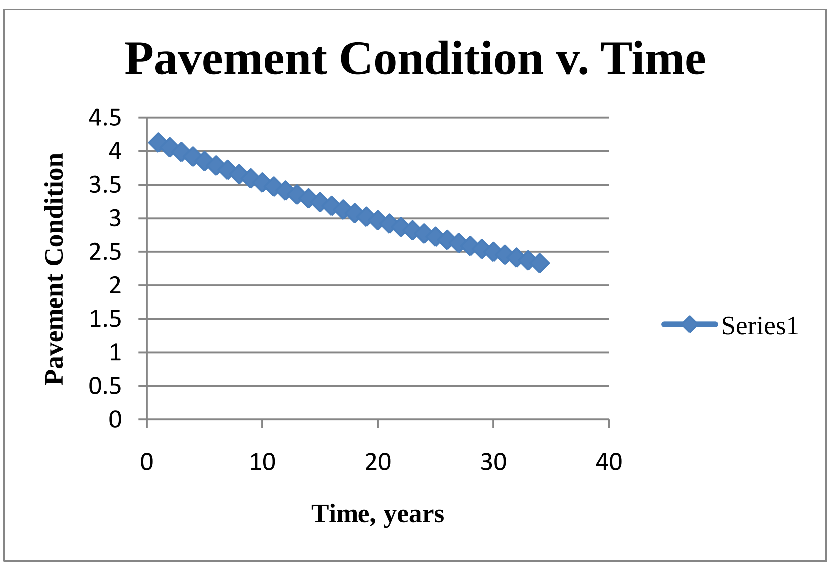


Figure 5.7: Pavement Condition with respect to time for environmental serviceability losses

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 lift axle trucks on pavement and bridge structures on Maryland roadways. Lift axle surveys were sent out to Departments of Transportations nationally to gain information on truck and lift axle policies nationwide. Analysis approaches based on their failure modes were conducted and applied to gain results on their effects on the bridge structure. Punching shear of a bridge deck of the structure was examined to look at the impact of the vertical forces of the single unit truck with tandem rear axles or tridem rear axle configuration. The yield line theory approach examined the transversal loading effects on the bridge deck. Also, the girder analysis allowed longitudinal analysis of the structure based on span length. Moreover, potential pavement damage was measured based on the axle loading of the truck.

The following summarizes findings for each failure mode:

- 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.

- For bridge deck moment check, the yield line theory exhibits that the tandem-axle configuration (4-axle truck with lift axle raised) has a bending moment approximately 2 times greater than that of the tridem-axle configuration.

- 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 the truck with the lift axle lifted when supposed to be deployed, the damage is about 3 times more than the damage of a tridem-axle case.

6.2 Conclusion and Recommendations

Overall, in each analysis approach, lift axle does have an effect on the behavior of both the bridge structure and the highway pavement. It is found that in almost all of the failure modes, the tandem axle or when the lift axle is raised, the weight carried by that axle is redistributed to the rear tandem axles. When this loading is redistributed to the tandem axles, this essentially puts higher stresses on the structure and thus creates higher moments and shears at those 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. If trucks are running at maximum weights and the axle is not deployed in accordance with Maryland, this creates not only non-compliance with state regulations, but even if the truck is not overweight, the redistribution still puts more stress on the tear tandem axles and potentially is more harmful to the structure. As for recommendations, Maryland State can propose regulations on lift axle configuration and set specifications for control systems. Making truck companies accountable for up-to-date technology and having an automatic lift axle control system will regulate based on axle weights, when the lift axle should be deployed or raised. Research on the most effective control device where the operator of the vehicle is not totally in control of the axle would be most efficient to behavior of the structure. Being that enforcement is difficult when it comes to these vehicles, the best means to regulate is to set new policies on axle configurations and control device specification.

Appendix A

Reference Tables and Graphs

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.

Figure A. 1: State Axle Weight Limits from NCHRP 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**	

Figure 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

Figure A.3: Table 6 of NCHRP 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

Figure A.4: Table 6 Continuation of NCHRP 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

Figure A.5: NCHRP Summary of State Posting that Exceed the Federal B Gross Weight Limits

Appendix B

Survey Results

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 trailor 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 reveiwed/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 eqipped with proper equpment 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 eqipped 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 occurences
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	

<u>Answer Choices</u>

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 which ever 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 Adminstrative 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	

Answer Choices

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 compleresearch 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	Straigh 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 C

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.

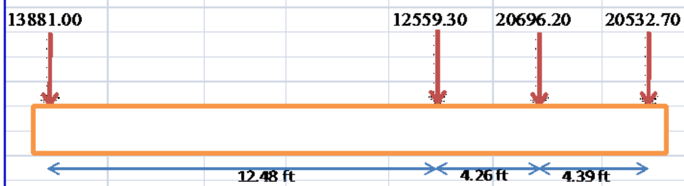
1. Direct division of individual blocks punching shear in 3 axle and 3 axle capacity for percentage loading in 3 i.e liftable axle.
2. The punching shear capacity for whole 2 axle block and % of indivudual punching shear and dividing it by whole 2 axle block capacity.
3. The difference between 3 axle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

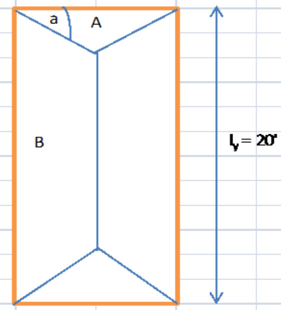
	By individual block method	By whole block method					
%Loading of Lift Axle	**Ratio 3axle/2 axle**	**Individua**	**Whole 2**	**Ratio**	**Whole block, lifta**	**Whole 2**	**Ratio**
20	**1.1**	26.6547	21.1945	**1.25762**	22.57196541	21.1945	**1.06499**
40	**1.2**	32.1149	21.1945	**1.51525**	23.9494009	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**

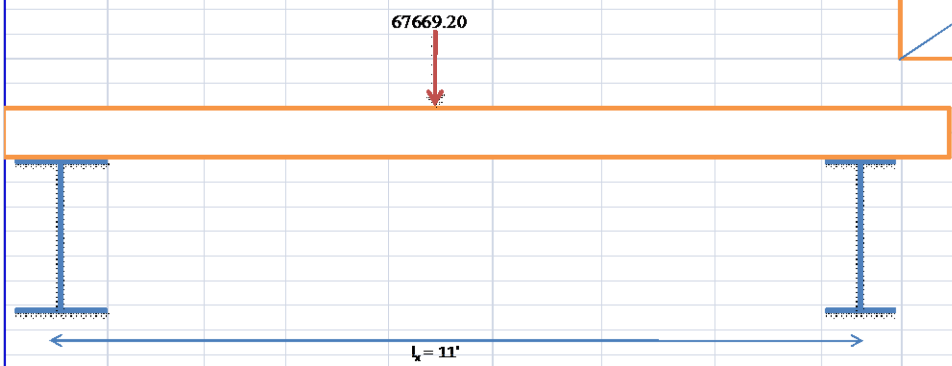
Yield Line Theory Calculations

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

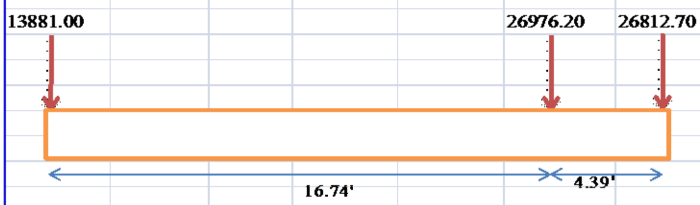
$$M_a^A = \frac{p \cdot l_x^2}{24} \tan^2 a \qquad M_a^B = \frac{p \cdot l_x^2}{8} - \frac{p \cdot l_x^2}{12} \frac{\tan a}{\lambda} \quad \text{with } \lambda = \frac{l_y}{l_x}$$

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

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

	Max Moment due to LL, For LRFD			LRFD	
S.L	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

	Max Moment due to LL, For LRFD			LRFD	
S.L	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

Lx	13.881
L2	1
pt	2.5
SN	4.42
Gt	-0.20091
Bx	0.477025
B18	0.569591

Log(Wtx/Wt18)		0.439874	
Wt18/Wtx		0.363183	ESALs
When Lx is on a single axle			
EALF	(Lx/18)^4	0.353666	ESALs

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

Assuming lift axle is raised

Truck Example 1: Tridem Axle

Lx	53.788
L2	3
pt	2.5
SN	4.42
Gt	-0.20091
Bx	0.567564
B18	0.569591

Log(Wtx/Wt18)	-0.21299	
Wt18/Wtx	1.633019	ESALs
When Lx is on a tandem or tridem		
(Lx/Ls)^4	1.576824	ESALs
Total Vehicle ESALs:	1.996203	ESALs

Assuming lift axle is deployed

Truck Example 1: Tandem Axle

Lx	53.788
L2	2
pt	2.5
SN	4.42
Gt	-0.20091
Bx	0.986184
B18	0.569591

Log(Wtx/Wt18)	-0.78824	
Wt18/Wtx	6.14105	ESALs
When Lx is on a tandem or tridem		
(Lx/Ls)^4	4.983541	ESALs
Total Vehicle ESALs:	6.504233	ESALs

<u>Flexible Pavement Model</u>: County 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	3.5		Axle Weights:	Axle 1	13,881	lbs
Gt	-0.20091			Axle 2	12,559	lbs
Bx	0.602262			Axle 3	20696.2	lbs
B18	0.845334			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		Truck Description			
Lx	13.881	Class	7		
L2	1	No. of Axles	4		
pt	2.5	Gross Weight	67,669		
SN	4.5	Axle Weights:	Axle 1	13,881	lbs
Gt	-0.20091		Axle 2	12,559	lbs
Bx	0.471385		Axle 3	20696.2	lbs
B18	0.557173		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

Bibliography

Alexander, S.B. and Hawkins, N. M. "Punching Shear in Reinforced Concrete Slabs: A Design Perspective on Punching Shear." American Concrete Institute. SP-232, (97-108). Farmington Hills, Michigan. 2005.

Altay, A., Arabbo, D., Corwin, E., Dexter, R., and French, C. "Effects of Increasing Truck Weight on Steel and Prestressed Bridges." University of Minnesota. Department of Civil Engineering. Minneapolis, MN 2003.

American Association of State Highway and Transportation Officials. (AASHTO). "AASHTO Guide for Design of Pavement Structures." Washington D.C. 1993.

Bai, Y., Schrock, S., Mulinazzi, T., Hou, W., Liu, C., and Firman, U. "Estimating Highway Pavement Damage Costs Attributed to Truck Traffic." University of Kansas Transportation Research Institute. Lawrence, Kansas. December 2009.

Beal, D.B., " Load Capacity of Concrete Decks." Transportation Research Record. Issue 871. Washington D.C. 1982 (70-74).

Billing, J., Nix, F., Boucher, M, and Raney, B. "On the Use of Liftable Axles by Heavy Trucks." Freight Transportation: Truck, Rail, Water, Hazardous Material. Transportation Research Record(TRR). Issue 1313, 1-10. Washington D.C., 1991.

British Columbia Ministry of Transportation (BC MTO). "Commercial Transport Regulations." British Columbia Reg. 206/2009. Commercial Transport Act. March 2010

.

California Department of Transportation. "Transportation Permit Policy Memorandum: Lift Axles". Office of Commercial Vehicle Operations and Permits. July 1999.

Chou, C-P J."Effect of Overloaded Heavy Vehicles on Pavement and Bridge Design."Flexible Pavement and Rehabilitation Issues. TRR, Issue1539, 58-65. Washington D.C. 1996.

Clayton, A. and Blow P. "Western-U.S.-Canada Cross border Case Study." United States Department of Transportation Comprehensive Truck Size and Weight Study, Report No. 5. Washington, D.C., December 1995.

Coalition Against Bigger Trucks. "Infrastructure Damage by Longer Combination Vehicles". http://www.cabt.org (2008).

Federal Highway Administration.(FHWA) "Bridge Formula Weights" U.S. Department of Transportation, Office of Freight Management and Operations. August 2006.

FHWA. "Commercial Vehicle Size and Weight Program" Freight Management and Operations. http://ops.fhwa.dot.gov/freight/sw/overview, May 2003.

FHWA. "Comprehensive Truck Size and Weight Study." Final Report , Volume I. Washington, D.C. August 2000.

FHWA. "Western Uniformity Scenario Analysis: A Regional Truck Size and Weight Scenario Requested by the Western Governors' Association." April 2004.

FHWA . "Truck Characteristic Analysis Study." Office of Highway Policy Information. Washington D.C. July 1999.

FHWA. "Vehicle Size and Weight. "Freight Management and Operations. April 2004.

Fu, G., Feng, J., Dekelbab, W., Moses, F., Cohen, H., Mertz, D. Thompson, P. Transportation Research Board. "Effect of Truck Weight on Bridge Network Costs." National Cooperative

Highway Research Program (NCHRP) Report 495. The National Academies. Washington D.C. 2003.

Gillespie, T.D., Karamihas, S.M., Cebon, D. et al. “Effects of Heavy Vehicle Characteristics on Pavement Response and Performance.” University of Michigan Transportation Research Institute. August 1992.

Green, C.A., Sproule, W. McNinch, T.L., Colling, T., and Benda, D. “Michigan State Log Truck Study” Michigan Technical University, Michigan Tech Transportation Institute. Houghton, Michigan. November 2005.

Hewitt, B. and Batchelor B., (1975) “Punching Shear Strength of Restrained Slabs.” Journal of the Structural Division., 1837-1853.

Huang, Y., “Pavement Analysis and Design.” 2nd Edition. Pearson Prentice Hall. Upper Saddle River, NJ. 2004.

Hveem, F.N. and Carmany, R.M. (1948), "The Factors Underlying the Rational Design of Pavements," Proceedings, Highway Research Board, Washington, D.C., December 1948.

Jones, L.L. and Wood, R.H., “ Yield-Line Analysis of Slabs” American Elsevier Publishing Company Inc. New York, NY 1967.

Lin, P., Wu, Y., Huang, T., and Juang, C. (1996) “ Equivalent Single-Axle Load Factor for Rigid Pavements.” Journal of Transportation Engineering. 122(6). 462-467.

Maryland Department of Transportation State Highway Administration. (MDSHA)“Impact of Dump Service Tag Vehicles on Maryland’s Roads and Bridges. March 1993.

Maryland Division of State Documents. *Code of Maryland Regulations*. (COMAR). 2003.

Maryland General Assembly. *Maryland Vehicle Law.* Maryland Division of State Documents Transportation Article. TR, 13-919. Annotated Code of Maryland.

Massachusetts Department of Transportation Highway Division(Mass Highway). *Bridge Design Manual*: Part I. June 2007.

Mertz, G.E., “Ultimate Capacity Evaluations of Reinforced Concrete Slabs Using Yield Line Analysis” Westinghouse Savannah River Company. Sponsored by U.S. Department of Energy. Aiken, S.C. November 1995.

Middleton, C.R. 1998 “Concrete Bridge Assessment,” presented at the Bridge Surveyor Conference (http://www-civ.eng.cam.ac.uk/brg/papers/brgsrv98/)

Millenbauch, P.J. (2009) “Over Weight Trucks” Construction Law News. Foster Swift Commercial Litigation Group. 1-4.

Mitchell, D, Cook, W.D., and Dilger, W. “Punching Shear in Reinforced Concrete Slabs: Effects of Size, Geometry and Material Properties on Punching Shear.” American Concrete Institute. SP-232, (39-55). Farmington Hills, Michigan. 2005.

Ontario Ministry of Transportation (ON MTO). “Vehicle Weight and Dimensions- for Safe Productive Infrastructure-Friendly Vehicles.” Ontario Regulation 413/05. Highway Traffic Act. December 2008.

Park, R. and Gamble, W. “Reinforced Concrete Slabs”. 2nd Edition. John Wiley & Sons, Inc. New York, NY. 2000.

Petrou, M., Perdikaris, P. (1996) “Punching Shear Failure in Concrete Decks As Snap- Through Instability.” Journal of Structural Engineering, 122(9) September 1996, 998-1005.

Quintas, V. (2003) “Two Main Methods for Yield Line Analysis of Slabs.” Journal of Engineering Mechanics, 129(2), 223-231.

Salama,H. K., Chatti, K. and Lyles, R.W. (2006) “Effect of Heavy Multiple Axle Trucks on Flexible Pavement Damage Using In Service Pavement Performance” Journal of Transportation Engineering., 132(10), 763-770.

Sivakumar, B., Ghosn, M. and Moses, F., “Protocols for Collecting and Using Traffic Data in Bridge Design.” NCHRP Project 12-76. The National Cooperative Highway Research Council, Transportation Research Board and National Research Council. Paramus, NJ 2008.

Sivakumar, B., Moses, F., Fu, G., Ghosn, M.,“Legal Truck Loads and AASHTO Legal Loads for Posting.” NCHRP Report 575. The National Academies. Washington D.C. 2007.

Saskatchewan Highway and Transportation. *Weights and Dimensions Administration Manual*. Saskatchewan Ministry of Transportation. April 2007.

Thomas, E.D. (2001) “Lift Axles: Are they the only way to comply with bridge formula laws?” Heavy Duty Trucking., 80(7), 76-80.

Transportation Research Board (TRB). Special Report 225 “Truck Weight Limits: Issues and Options.” TRB Special Report 225. National Research Council. Washington D.C.

TRB. “New Trucks for Greater Productivity and Less Road Wear” TRB Special Report 227. National Research Council. Washington D.C. 1990.

Washington State Department of Transportation (WSDOT). Koehne, J. and Mahoney, J. “An Evaluation of the Lift Axle Regulation in Washington” WAC 468.38.280 Final Technical Report. Washington State Transportation Commission Transit, Research, and Intermodal

Planning Division with U.S. Department of Transportation Federal Highway Administration(FHWA), June 1994.

Weber, R. " Push in Canada for Lift Axle Rule Harmonization". Trailer Body Builders. http://trailer-bodybuilders.com, February 2007.

WSDOT. "Legal Load Limits, Overweight Loads and Pavements and Bridges." Washington, June 2006.