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Development of Advanced Weigh-In-Motion (A-WIM) System for Effective Enforcement of Overweight Trucks to Reduce their Socioeconomic Impact on Major Highways

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Executive Summary

The U.S. has over 600,000 bridges and 4 million miles of roadways across the entire nation. The American Society of Civil Engineer (ASCE) reported that the average infrastructure score is D+, which denotes the infrastructure is in poor to fair condition and mostly below standard, with many elements approaching the end of their service life (ASCE, 2020). Among different infrastructures, bridges and roadways are the critical elements because approximately 63% or more freights were transported via trucks, followed by rails (15%) and others (pipelines, air, vessel/ship, etc.) in 2017 (USDOT, 2020). Almost 40% of bridges in the U.S. are more than 50 years old, over 9% of bridges are structurally deficient in 2016, and over 21% of pavement sections are in poor condition in 2017. There are many causes for the current state of the bridges and pavements; nonetheless overloading from overweight trucks (permits and illegal) would be one of the most critical reasons that could be controlled by balanced regulations and policies and effective automated enforcement.

The roadway infrastructure continuously deteriorates as they are exposed to heavy trucks. The effect of truck loads on the infrastructure (bridges and pavements) is essential to upgrading and maintaining the transportation infrastructure. Overweight (OW) trucks induce significant damage and cause noticeable deterioration on pavements and bridges that results in frequent maintenance schedules and more rehabilitation costs. The local transportation agencies are continually searching for ways to optimize OW trucks' regulation while promoting commerce and movements of goods and services. Moreover, agencies issue permits for overweight trucks with the goal that these permit fees will supplement the funds allocated for repair, maintenance, and rehabilitation. However, one primary concern is whether the agency's permit revenues can recoup the cost of the actual damage incurred by these permits on the infrastructure. The team received permit records from 2013 to 2018 from NJDOT and extracted the OW permit records, which has the gross vehicle weight of more than 80 kips. Based on the analysis tool developed by the team (Nassif et al., 2018), the team estimated the bridge as well as pavement damages due to these trucks and compared the revenues with the permit fees. The analysis shows that the damage costs for bridges and pavement were about 37% and 63% of the total damage cost due to the OW permit trucks, respectively. The total damage attributed to bridge structures was \$1.7 million per year, while the damage cost to pavement was \$2.9 million per year. The OW permits consist of two types – single OW permits with paid OW tonnage fee and single OW permits with Code 23 registration. The latter is designed for the trailers that transport the divisible load and are not required to pay the OW tonnage fee. The first type paying the OW tonnage fee is approximately 46% of the total single OW permits. Therefore, the infrastructure damage cost associated with the “paid” single OW permits is approx. \$2.1 million per year. Similarly, the OW permit revenue was also determined based on the New Jersey permit schedule. The OW permit fees were added up to \$2.1 million per year, which is almost the same as the infrastructure damage cost. Therefore, NJ's current permit fee schedule would be able to recoup the damage due to the OW trucks with single permits. The same single OW permit records were

applied to all other states, and it was found the NJ is ranked as the 4th highest state in permit fees among 50 states and D.C. The infrastructure damage cost would differ between states, but the extent would not be different in the 10th order. Thus, other states' permit fee schedule needs to be updated to recoup the damages due to the OW and permit trucks.

The PVDF sensor is very susceptible to changes in pavement temperature, and the accuracy will be affected depending on the environmental conditions. Therefore, the calibration of the WIM system is a critical step in improving the accuracy of WIM data. The procedure must also cover the annual temperature variation over the four seasons to reach more reliable calibration factors. Since the pavement temperature is not always measured in-situ, this report presented a methodology to estimate the pavement temperature based on the ambient temperature, which is still available from a nearby weather station. It was found that the estimated maximum pavement temperatures provide a better approximation than the minimum pavement temperatures. When the pavement temperature is not available, the estimated pavement temperature can effectively compensate for the temperature effect on the accuracy of the WIM data. The adjustments applied to the WIM data using this proposed approach provide very close accuracy as when the WIM data is corrected by the measured pavement temperature.

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Section 1: Introduction

The effect of truck loads on the infrastructure (bridges and pavements) is essential in the effort of upgrading and maintaining the transportation infrastructure. Overweight (OW) trucks induce significant damage and cause noticeable deterioration on pavements and bridges that results in frequent maintenance schedules and more rehabilitation costs. Early studies on the impact of heavy truck loads on road pavement were performed by the AASHTO Road tests performed in the 1950s. Test data have shown that the damage on pavements can be as significant as to the fourth power of the loads. The C2SMART Project (Monitoring and Control of Overweight Trucks for Smart Mobility and Safety of Freight Operations) by the Rutgers RIME team conducted a study to evaluate the infrastructure damage induced by the overweight trucks in New Jersey (NJ) and New York City (NYC). The study showed that the pavement damage cost could be expressed by the equivalent single axle load (ESAL), which converts damage from wheel loads of various magnitudes and repetitions to damage from an equal number of “standard” or “equivalent” loads of 18,000 lb. Accordingly, the damage per the unit pavement damage cost for highway pavement in NJ varies from \$0.027 to \$0.052/ESAL-lane-mile.

In contrast, the unit pavement damage cost on the highway corridor in NYC ranges from approximately \$0.0345 to 0.0698/ESAL-lane-mile. On the local roads, higher pavement damage costs are estimated as the local roads were designed to carry lighter loads than highway corridors. It shows that the unit pavement damage cost ranges between \$0.092 and 0.483/ESAL-lane-mile in NJ and between \$0.117 and 0.648/ESAL-lane-mile in NYC. The team also found that the unit bridge damage cost in NYC is continuously higher than for most NJ highways because local labor and material cost in NYC would be higher than NJ according to RSMMeans report (2012a, 2012b). The unit damage cost of overweight trucks for the reinforced concrete (RC) bridge decks, steel multi-beam girders, and steel girder-floorbeam girders of the local roads in NJ was 146%, 327%, and 361% of the maximum damage cost found in NJ, respectively (Nassif et al., 2015; Lou et al., 2016; Lou et al., 2017). It was concluded that the damage analysis was not enough due to the amount of data and the quality of information available at the time of the analysis. Additional weight-in-motion (WIM) sites are required for a comprehensive evaluation of the impact of OW trucks on the entire NYC infrastructure network.

Permits help regulate the operation of OW trucks as well as oversized (OS) trucks by ensuring the safety of infrastructure and minimizing damage to infrastructure while promoting commerce and the movement of goods and services. Currently, each state regulates the OW/OS trucks by encouraging them to obtain different types of permits, which are imposing fees based on each state regulatory policy or fines by enforcing at weighing stations. In the case of New York City and State, the legacy OW/OS permits are grandfathered, and no additional permits are issued over the last decades. The OW permit comes with a flat fee of \$40 regardless of its extent of the load. However, New Jersey has a more comprehensive permit fee structure depending on OW/OS. Single permits were issued to OW and/or

OS trucks depending on the extent of load and size. New Jersey also requires registering the trailers (so-called Code 23) for a single permit and issues the Ocean Borne Container permits for multiple travels. Permits and registration have been regulated by imposing an excess tonnage fee under the NJ permit fee system. Different states have their own permit fee structure depending on their policy for moving goods and services, and the current fee structure would not intend to recover the damage cost induced by the OW trucks. Nonetheless, they encourage the truck owners to get permits so that the state can manage such vehicles (Nassif et al. 2015).

A considerable number of WIM stations use the piezoelectric polymer (polyvinylidene fluoride or PVDF) sensor to measure the weights of trucks because of easy handling and installation and low installation and maintenance costs (Demiroglu et al. 2018). However, PVDF sensors are not very accurate and are affected by the environmental condition. Since piezoelectric material uses the mechanical stress generated by the tire of a truck to measure the axle weight, the stiffness of the pavement has a significant influence on the final estimation of the load, and the pavement temperature is one of the critical factors that affect pavement stiffness. The main variables that are susceptible to distortions by the temperature variations are the axle weights and gross vehicle weight. Thus, measurements of pavement temperatures are required to improve the accuracy of the WIM data. Although the pavement temperature has a crucial role in the accuracy of weights estimation, it is not usual to instrument the temperature sensors at WIM stations because of its additional cost to install and manage. Alternatively, ambient temperature is always available at nearby weather stations. Therefore, an approach capable of using ambient temperature to estimate pavement temperature is highly valuable when trying to improve the accuracy of WIM data.

This report synthesizes the research effort for estimating the infrastructure damage due to OW permit trucks and developing a methodology to minimize the error in weighing the GVW and axle weight for future enforcement practice in the NYC metropolitan area.

Subsection 1.1: Objectives

The main objectives of this project are (1) to evaluate the infrastructure damages incurred by the overweight permit trucks, (2) to compare the permit policies between states to check understand how each state handles the OW permits, and (3) to develop the methodology to minimize the error in weighing the truck weight (gross vehicle weight and axle weight). These objectives are designed to advance the final purpose, which is to establish a testbed in New York City or New Jersey and to develop an integrated autonomous enforcement system for screening trucks for overweight violations.

Section 2: Literature Review

The most relevant literature related to the quality control and quality assurance (QA/QC) of WIM data and methodologies to improve the weight accuracy, WIM specifications and standards, and enforcement practices were reviewed. Technical papers, as well as research work done by FHWA, NCHRP, and state DOT were reviewed and compiled. The available WIM specifications and standards in the US and Europe were reviewed, and different enforcement practices in the US and foreign countries were also studied.

Subsection 2.1: QA/QC of WIM Data

The WIM data includes several measurement errors due to various reasons that need to be recognized and considered in the data review process. However, many WIM sensors demonstrated acceptable results in the laboratory environment. However, the WIM sensors rarely show the same accuracy as the laboratory when they are deployed on the pavement. There are many causes for poor quality WIM data from the vehicle characteristic (suspension, acceleration, braking, change lanes, etc.) to the environmental condition (pavement level, pavement roughness, pavement condition, pavement material, etc.). The installation environment highly affects sensor performance and accuracy. Piezoelectric sensors show different performances in the US and Europe because different climates and temperatures of two continents affect the footprint of the signal from the vehicle (Koniditsiotis, 2000).

The followings are the possible reasons for errors, which might occur in comparison to static wheel load scales. Researchers will be able to understand the performance and behavior of WIM systems. The primary sources of errors could be classified below:

1. Suboptimal WIM site choice: The accuracy of the WIM sensor is dependent on the noise level. Various sources of vibration produce enormous noises in the sine wave signal of the WIM sensor. As the noises are dependent on the pavement condition, it is crucial measuring the international roughness index (IRI), falling weight deflectometer (FWD), pavement surface profiling, etc. It would be of prime importance before any installation of WIM sensors for selecting the best site and continuing maintenance of the site (Middleton et al. 2004).
2. Calibration drift due to temperature: The gross vehicle weight (GVW) and the front axle weight (FAW) for Class 9 increases as the pavement temperature increases. When the pavement is subjected to a higher temperature, the pavement will be more flexible, and such flexibility of the pavement results in a higher amplitude of the WIM signal.

3. Calibration drift due to time: Pavement and epoxy degrade over time, and any change in their mechanical properties would affect the signal strength and waveform of the WIM sensor. Since the WIM sensors are calibrated at a specific time and season, the WIM system may lose the ability to measure the weight correctly.
4. Settings or Dimensions: Inaccurate sensor location, improper installation, and wrong system settings may result in the low quality of WIM data.
5. Vehicle characteristics: Vehicle speed, acceleration, and deceleration affect the WIM accuracy, especially at a higher speed because the road imperfections may affect more significantly to the vehicle suspension. Moreover, changing lanes and bypassing partial WIM sensors would be another concern that would affect WIM accuracy.

WIM data must be quality checked before the data processing to establish a dataset for providing sound and valid data for any analysis. Therefore, the collected WIM data requires a quality control check before analyzing the data to verify the data quality.

Subsection 2.1.1: WIM Filters (NCHRP 12-83)

WIM is prone to various errors that need to be identified and managed in the data review process. There are multiple reasons for questioning the data; for example, GVW is too low, unrealistic configuration, too fast speed, etc. Filtering would remove the unreliable data and unlikely trucks to ensure data quality for any future analysis. Therefore, it is essential to develop filters to eliminate suspicious vehicles. In the context of such efforts, NCHRP report 683 established a statistical algorithm to filter out the erroneous WIM data to establish the load modeling process (Bala et al., 2011). The report tried to remove slow-moving traffic (< 10 mph) and stop-and-go traffic because slow speed might disturb the footprint of the WIM signal. It also assumed the maximum likely axle spacing as trucks with large axle spacings and excessive total wheelbase may be a combination of two vehicles. Accordingly, the report developed the following criteria to clean up WIM data.

- Speed <10 mph
- Speed >100 mph
- Truck length >120 ft
- Total number of axles <3
- Record where the sum of axle spacing is greater than the length of truck
- GVW <12 kips
- Record where an individual axle is >70 kips
- Record where the steer axle is >25 kips

- Record where the steer axle is <6 kips
- Record where the first axle spacing is <5 ft
- Record where any axle spacing is <3.4 ft
- Record where any axle is <2 kips
- Record which has GVW +/- sum of the axle weights by more than 10%

The filtering criteria were further updated in the NCHRP 12-83 “Calibration of AASHTO LRFD Concrete Bridge Design Specifications for Serviceability” as the WIM data from NCHRP 12-76 include many vehicle records that appear to be incorrect (Wassef et al., 2014). An additional filter (the sum of the axle spacing lengths is less than 7 ft.) was added based on a study by Pelphrey et al. (2008). This report then checked the exceptionally heavy vehicles that comply with all filtering criteria if their configuration resembled permit vehicles, such as cranes and garbage trucks. Accordingly, vehicles considered to be permit vehicles and illegally loaded trucks were filtered using the following criteria. Figure 1 shows the NCHRP 12-83 filter (Wassef et al., 2014).

- Total number of axles less than 3 and GVW is more than 50 kips
- Steering axle weight is more than 35 kips
- Individual axle weight is more than 45 kips

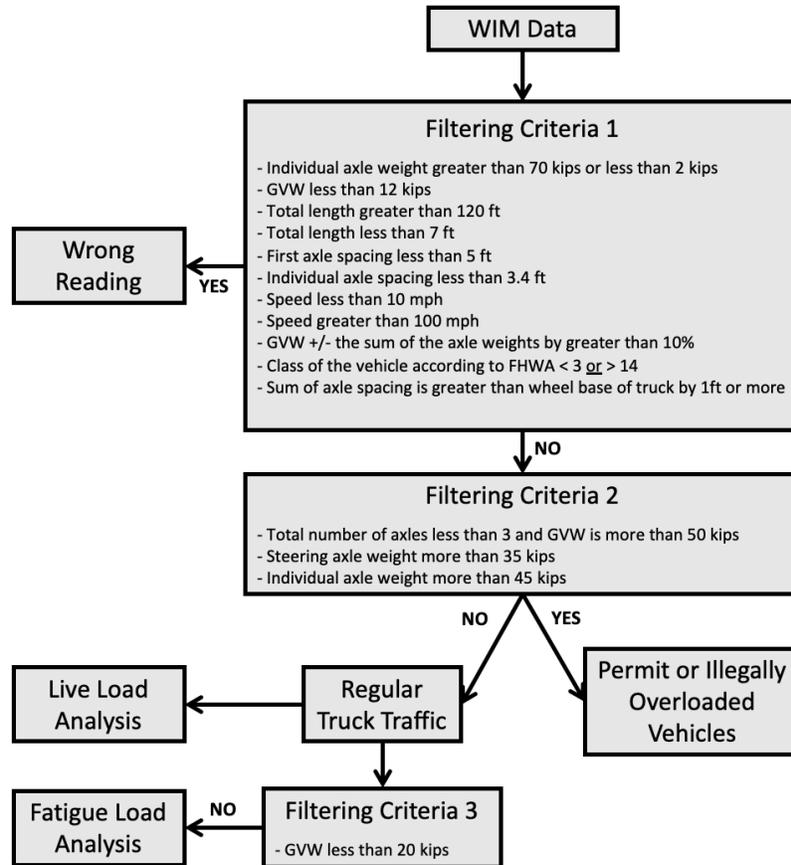


Figure 1: NCHRP 12-83 Filter (Wassef et al, 2014)

Subsection 2.1.2: WIM System Calibration using Class 9 (Type 3S2, Semi-Tractor Trailer)

Dahlin (1992) offered a practical method to calibrate a WIM system explicitly based on the steering axle weights (or front axle weights, FAW) and gross vehicle weights (GVW) of FHWA Class 9 trucks. FAW and GVW data produced by the sensors were used to control any drifts from various parameters such as climate and traffic conditions. The bimodal distribution validated GVW, and FAW was confirmed by the average steering axle weight per three GVW categories (Dahlin, 1992).

Ott and Papagiannakis (1996) discussed issues with the method of Dahlin, indicating that since the estimated GVW of 3S2 trucks was summations of weight estimations of the axles, the error of GVW estimation would be lesser than the error of estimate for each axle. This is because each axle weight could diminish the errors in the GVW. Also, the method is based on the distribution of GVW and does not consider other factors. Extensive analyses between the years 1974 to 1983 for static data of the 3S2 trucks (GVW and FAW) from 976 sites were also discussed. The results showed that close to 80% of the sites had bimodal load patterns (including two peaks for unloaded and loaded trucks), 14% unimodal (loaded), 4% unimodal (unloaded), and 2% multimodal (more than two peaks) (Ott et al.,1996).

Several studies have been performed specifically for WIM data quality control and quality assurance (Southgate, 2001; Wei et al., 2003; Nichols et al., 2004; Turner, 2007; and Monsere et al., 2008). For instance, Nichols et al. (2004) proposed a WIM data quality control (QC) method to check axle spacing and weight accuracy using FAW and drive tandem axles of 3S2 trucks. The procedure was recommended as an alternative calibration method by a speed radar gun where this device cannot be used for a variety of reasons, such as on high-traffic highways.

Subsection 2.1.3: Southgate Regression

It is a very well-known approach for QA/QC to use the regression analysis proposed by Southgate (2001). It utilizes a logarithmic regression of axle spacing and weights to validate the WIM calibration. The procedure is applied to Class 9 (Type 3S2, semi-tractor trailers) because the properties of the FAW are mainly related to the drive tractor and not the payload. Further, Class 9 vehicles are the same used by most WIM systems for auto-calibration. This approach takes the ratio of the FAW over the first axle spacing (S12) of FHWA Class 9 trucks and compares the regression curve obtained to a reference equation. Detailed information is described in the report entitled “Quality Assurance of Weigh-In-Motion Data” (Southgate, 2001). If the regression curve of all Class 9 falls within the upper and the lower boundary and close to the reference equation, then the WIM data has a good data quality. Chou et al. (2016) used a similar method to minimize WIM error. In their work, the adjustment process utilized time series analysis and removes temperature-induced variations in the estimation of weights. After following the approach in Southgate (2001), the correction factors derived from Class 9 trucks by an hour and day were applied to the trucks recorded by the WIM system during the same period.

In the Southgate approach, the reference equation is set on a log-log scale. It has an upper limit of 12 kips for the front axle that was obtained using data from many trucks in Kentucky, and a lower limit based on the regression curve. The Southgate reference line equation is shown in (Eq. 1).

$$FAW/S12 = 10^{(3.925361 - 0.952182 \times \log_{10}(S12))} \quad (\text{Eq. 1})$$

The upper bound curve is also proposed whereby the equation is applied on the limiting 12 kips of FAW (per manufacturer’s specification) plus 50 kips. (Eq. 2) shows the upper bound curve of Southgate regression.

$$FAW/S12 = 12000/S12 + 50 \quad (\text{Eq. 2})$$

The lower bound curve for the data is also obtained from truck manufacturers’ data and shown in (Eq. 3).

$$FAW/S12 = 10^{(3.942369 - 1.07509 \times \log_{10}(S12))} \quad (\text{Eq. 3})$$

If the regression curve of all Class 9 falls within the upper and the lower boundary and close to the reference equation, then the quality of WIM data is acceptable.

Subsection 2.2: Estimation of Pavement Temperature

As the temperature variation strongly influences PVDF sensors, compensation of these effects must be considered to measure the weights of trucks accurately. Accordingly, one standard procedure is to perform a calibration test with a known weight truck. In this methodology, the truck crosses the WIM station several times at different speeds and times of the day. The system response is recorded and compared with the weight of the truck (measured on a static scale), and then adjustment of the system is made. One major disadvantage of this practice is that to obtain a reliable set of correction factors (also known as calibration factors), the truck must cross the WIM sensors in a different range of temperatures; preferably, the temperature ranges should cover the temperature variations for one year. On one side, waiting one year to have reliable calibration factors may not be an acceptance by the owner of the road. On the other side, using the results from calibrations performed during summer, for example, to adjust WIM data recorded during winter might not help at all. Thus, it is important to measure the pavement temperatures to update the WIM data and improve its accuracy. The piezoelectric material of the PVDF sensor is designed to generate the electric signal by the *uniaxial* mechanical stress. When the temperature is high, the pavement is more flexible, and both horizontal and vertical pressures would force the PVDF sensor. Therefore, the stiffness of the pavement has a significant influence on the final estimation of the load. According to Huang (2004), for hot-mix asphalt (HMA) at higher temperatures, the pavement is more viscous. In this case, the load of a truck transmitted to the sensors is larger than the load for lower temperatures. Although the pavement temperature has a vital role in weights estimation accuracy, it is not usual to instrument the temperature sensors at WIM stations. This is mainly due to the additional effort required to instrument thermocouple(s) at a depth of WIM sensors and a logging system to collect the temperatures. Alternatively, ambient temperature is always available at nearby weather stations.

Several works aim to develop models to predict the pavement temperature from ambient temperature (Barber, 1956; Rumney et al., 1971; Solaimanian et al., 1993; In et al., 2004; Diefenderfer et al., 2006). Barber proposed the first study on the estimation of maximum pavement temperature in 1957. As his model was simple and incorporated with the total daily radiation and daily air temperature range, this model was advanced by incorporating the hourly radiation to predict the pavement temperature at 2 in. deep (Rumney et al., 1971). Later, another comprehensive equation was developed to estimate the maximum pavement temperature (Solaimanian et al., 1993). In his model, various coefficients related to solar energy, thermal conductivity, radiation, heat transfer, etc. were accounted for maximum and minimum pavement temperatures. This model was implemented to calculate the maximum and minimum pavement temperatures for a couple of sites in Korea (In et al., 2004). A simplified equation

was proposed that incorporates a limited number of variables such as ambient temperature, pavement depth, hourly solar radiation energy, and latitude (Diefenderfer et al., 2006). The models were proposed based on Virginia Smart Road data and then validated using other states' data. The results from previous studies show that the pavement temperature is correlated with the ambient temperature, but the surface temperature is affected by the thermodynamic properties of the surface materials, which incorporates surface moisture, thermal absorption and emission, and radiative input from the sun and atmosphere, etc. (Voogt et al., 2003). Therefore, the pavement temperature is a site-specific characteristic, and the correlation for one site is not appropriate to apply for another site.

According to Voogt (2003), pavement temperatures are affected by the pavement's thermodynamic properties, such as thermal radiation and absorption. It is also a function of the environmental condition, such as solar radiation, ambient temperature, wind speed, and precipitation. It is also a function of the environmental condition, such as solar radiation, ambient temperature, wind speed, and precipitation. Among the environmental conditions, solar radiation and ambient temperature are the major parameters that affect the pavement temperature. These temperatures are site-specific information, and the estimation of them for one place may not apply to another one as the solar radiation varies for latitude. Daily maximum and minimum pavement temperatures were estimated based on the ambient temperature incorporating solar absorption and radiation (Diefenderfer et al. 2006). In their work, they developed a model conducted within the Virginia Smart Road project. They used two Long Term Pavement Performance (LTPP)-SMP sites to validate their equations, which included as variables the day of year and latitude of the site. The developed equation can only be used for asphaltic pavements and can only estimate the maximum and minimum temperatures for each day. The model proposed by Diefenderfer et al. (2006) was developed based on a statistical analysis of observed data to estimate maximum and minimum daily pavement temperature. The proposed model (for hot-mix asphalt, HMA only) considers variables such as latitude of the site, solar radiation, ambient temperature, and depth within the pavement as follows:

$$T_p = a + bT_a + cR_s + dP_d \quad (\text{Eq. 4})$$

where T_p = the estimated pavement temperature (°C)

T_a = the measured ambient temperature (°C)

R_s = the calculated solar radiation (kJ/m²-day)

P_d = the depth within pavement (m)

a = the intercept coefficient

b = the ambient temperature coefficient

c = the calculated solar radiation coefficient

d = the depth coefficient

The daily solar radiation on a horizontal surface, R_s , can be calculated by Equation (5) which is a function of the day of the year, latitude, sunrise angle, and eccentricity factor.

$$R_s = (24/\pi) I_{sc} E_o \sin(\varphi) (\delta) [(w_s \pi)/180 - \tan(w_s)] \quad (\text{Eq. 5})$$

where I_{sc} = the solar constant (4,871 kJ/m²-h)

E_o = the eccentricity factor

φ = the latitude (deg)

δ = the solar declination (deg)

w_s = the sunrise angle.

From Equation (4), the linear regression can be determined by incorporating the maximum ambient temperature, daily solar radiation, and sensor depth. The maximum and minimum pavement temperatures are proposed, as shown in Equations (6) and (7), respectively.

$$T_{p \max} = 2.78752 + 0.6861T_{a \max} + 5.6736 \times 10^{-4}R_s - 27.8739P_d \quad (\text{Eq. 6})$$

$$T_{p \min} = -1.2097 + 0.6754T_{a \min} + 3.7642 \times 10^{-4}R_s + 7.2043P_d \quad (\text{Eq. 7})$$

where $T_{p \max}$ = the maximum daily ambient temperature

$T_{p \min}$ = the minimum daily ambient temperature

With the estimated maximum and minimum pavement temperature for each day, interpolations for each hour can be performed to assess the pavement temperature for each hour. Based on the FWA of Class 9 trucks and estimated pavement temperature, a relationship between FAW and pavement temperature could be derived. If the same relationship between axle weight and pavement temperature, each truck weight could be adjusted per estimated pavement temperature.

Subsection 2.3: Weigh-In-Motion (WIM) Standards

There are several WIM standards in the US and Europe to improve the accuracy of the WIM system and to minimize any argument on the enforcement. There are two WIM standards in the US and two other WIM standards in Europe to characterize or classify WIM systems:

Subsection 2.3.1: ASTM E-1318 Standard Specification for Highway Weigh-In-Motion Systems with User Requirements and Test Methods (2017)

ASTM E1318 defines that the WIM is the process of estimating a moving vehicle’s gross weight and the portion of that weight carried by each wheel, axle, or axle group, or a combination thereof, measurement and analysis of dynamic vehicle tire forces. It defines the functional performance requirements for WIM systems, as summarized in Table 1 in four different types of WIM systems, Type I, Type II, Type III, and Type IV. Among these types, the Type III system is intended for enforcement purposes at high speed, while the Type IV system defines the enforcement at a static scale. The ASTM E-1318 is intended to facilitate the relationship between a buyer and a vendor in non-legal applications.

Function	Wheel Load	Axle Load	Axle-Group Load	Gross-Vehicle Weight	Speed	Axle-Spacing and Wheelbase
Type I	±25% ^A	±20%	±15%	±10%	±1 mph (2 km/h)	±0.5 ft (0.15 m)
Type II	N/A	±30%	±20%	±15%		
Type III	±20%	±15%	±10%	±6%		
Type IV						
Value ≥ lb ^B	5,000	12,000	25,000	60,000		
± lb	300	500	1,200	2,500		
Remarks	A. Tolerance for 95% Compliance. 95% of the respective data items produced by the WIM system must be within the tolerance.					
	B. Lower values are not usually a concern in enforcement					

Table 1: Performance Requirement in ASTM E1318

Subsection 2.3.2: NIST Handbook (HB) Section 2.25 Weigh-in-Motion Systems used for Vehicle Enforcement Screening (2020)

This is a tentative code and is not intended to be used for enforcement yet. The requirements are designed before the development and adoption of the final code. NIST 2.25 set the tolerance values for the dynamic load test, as summarized in Table 2. The GVW, axle weight, and tandem weight tolerances for accuracy Class A are set for 10%, 20%, and 15%. Such tolerances are similar to Type I of ASTM E1318.

Tolerance as a Percentage of Applied Test Load

Load Description*	Axle Load	Axle-Group Load	Gross-Vehicle Weight
Class A	±20%	±15%	±10%
* No more than 5% of the weighments in each of the load description subgroups shown in this table shall exceed the applicable tolerance.			

Table 2: Performance Requirement in NIST 2.25

Subsection 2.3.3: COST 323 European WIM Specification (2002)

The European Cooperation in Science and Technology (COST) Action 323 applies to Low Speed (LS) and High Speed (HS) WIM systems for all applications, but not for the trade of systems. Although it is formally not an official international standard, it is widely used as a reference in the testing and acceptance of WIM systems by manufacturers and users. It explains that a WIM system's accuracy under moving traffic tire loads may only be defined statistically by a confident interval of the relative error of a unit (an axle, an axle group, or a gross weight). The error is defined by $(W_d - W_s)/W_s$, where W_d is the impact force or dynamic load measured by the WIM system and W_s the corresponding static load/weight (or any other specified reference value) of the same unit. Such a confidence interval centered on the static load/weight, is noted: $[-\delta, +\delta]$, where δ is the tolerance for a confidence level π (for example, 90 or 95%). COST 323 defines the accuracy requirements for weight, as summarized in Table 3. It shows that the accuracy for enforcement to be 5~10% of δ (class A(5) or B+(7)).

Criteria	Domain of Use	Accuracy Classes: Confidence Interval Width δ (%)						
		A(5)	B+(7)	B(10)	C(15)	D+(20)	D(25)	E
Gross Weight	> 3.5 t	5	7	10	15	20	25	> 25
Axle Load	> 1 t							
Group of Axles		7	10	13	18	23	28	> 28
Single		8	11	15	20	25	30	> 30
Axle of a Group		10	14	20	25	30	35	> 35
Speed	> 30 km/h	2	2	4	6	8	10	> 10
Inter-axle distance		2	3	4	6	8	10	> 10
Total flow		1	1	1	3	4	5	> 5

Table 3: Accuracy Tolerance in COST 323

Subsection 2.3.4: OIML R-134 Automatic instruments for weighing road vehicles in motion (2003)

This recommendation is intended to use for enforcement and trade. In some countries, like the Czech Republic, France, Brazil, and Switzerland, there is an existing type of approvals based on local laws that use such systems on main roads. The OIML R134 standards specify the requirements and test methods for automatic instruments for weighing road vehicles in motion to determine the total vehicular weight and test procedures to evaluate the technical characteristics of the WIM system. The OIML R134 defines the maximum tolerance error in percentage in the initial verification stage and in-service stage, which are summarized in Table 4.

Accuracy Class	Percentage of Mass of Total Vehicle (%)	
	Initial Verification	In-service Inspection
0.2	±0.10	±0.20
0.5	±0.25	±0.50
1	±0.50	±1.00
2	±1.00	±2.00
5	±2.50	±5.00
10	±5.00	±10.00

Table 4: Maximum Permissible Error in OIML R134-1

Most WIM systems in the US are targeting the Type I accuracy, according to ASTM E1318, that complies with federal reporting requirements. However, the enforcement shall comply with the requirement per ASTM E1318 Type II, COST323 A(5), and OIML R134 Accuracy Class 5.

Subsection 2.3.5: Comparison of WIM Standards

Four standards, (1) ASTM E1317, (2) NIST 2.25. for WIM in the Handbook 44, (3) OIML R134, and (4) COST 323, are compared and summarized in Table 6. The following observations were concluded while comparing four standards:

- **ASTM E1318** would be a good starting point to develop the specification as it covers the majority aspects of WIM enforcement, but it is not as detailed as COST 323 and OIML R134.

- **NIST 2.25** for WIM is not detailed enough for WIM enforcement because this is developed initially based on the Scale Specification (Section 2 is dedicated to Scale).
- **OIML R134** is too strict and requires 100% compliance requirement at very low error.
- **COST 323** would be an excellent example to adopt, but it requires a significant amount of calibration runs, and it may need some modifications for adoption in the USA as it is designed for Europe.

1- NIST Spec is designed for Class A, which is equivalent to ASTM Type I (GVW 10% and Axle 20%). COST 323 Class B(7) is almost equal to ASTM Type III. Three needs 95% compliance, while OIML R134 requires a 100% compliance. See Table 5 for the comparison of accuracy tolerance between standards.

2- At least two calibration trucks are required in NIST spec: Class 9 (GVW = 80 kips, mandated) and Class 5 (GVW < 10 kips, optional) with 85-95% loading. However, ASTM Type III requires two Class 9 calibration trucks - one 3S2 and the other 3S2-Split with at least 90% of registered GVW (in general 72 kips). OIML R134 requires a Class 6 truck and minimum 2 additional trucks (Class 5/6 with a drawbar trailer, Class 6~7, or Class 8 ~10) with loaded and unloaded. COST 323 requires a minimum 3-4 trucks according to European Classifications, which are similar to Class 3, Class 5/6/7 (with and without a trailer), and Class 8/9/10.

3- NIST requires a minimum 40 runs in total or 20 runs per truck. This includes 5 runs on each edge of the road and 10+ runs in the middle of the road per truck. However, ASTM requires a minimum of 20 runs in total or 10 runs per truck. This includes 5 runs each at low and high speed per truck, and it requires at least 1 run on each edge of the road at each speed (low and high) regardless of trucks. OIML R134 mandates a minimum of 90 runs in total or 30 runs per truck. This includes 5 runs at 3 speeds and loaded/unloaded conditions. COST 323 mandates a minimum of 110 runs in total at Test Plan N°2.2/N°3 with 2-3 speed levels and loaded/unloaded conditions.

4- The calibration test for NIST Spec shall be performed 20% below or at the posted speed while that for ASTM shall be performed 5 mph below the maximum, and 5 mph above the minimum posted speed. OIML-134 requires 3 speeds at minimum operation speed, maximum operation speed, and mid-speed of minimum and maximum. COST 323 recommends 3 speeds at mean speed, 80% of the mean speed, and 120% of the mean speed of the site.

5- ASTM requires a Type-Approval Test Loading for 51 vehicles (randomly selected of Class 5 ~ Class 13 from normal traffic, other than calibration trucks) for any Type approval (Type I, II, III, and IV) before the calibration test, while NIST has no such requirement. OIML R134 requires an initial verification after the calibration test using the same procedure as a calibration test with different reference trucks. COST 323 requires a Type Approval Test for Site Class 1 (Enforcement purpose) with a limited number of trucks before the calibration test.

6- ASTM recommends preparing the surface 200 ft before and 100 ft after WIM sensors. OIMLR134 mandates to make the concrete or rigid apron 55 ft before WIM sensors. COST 323 defines the Site Class I~III depending on the rutting and IRI, and they are very details. However, NIST does not specify any site conditions.

Standard	Accuracy Tolerance	Reference
ASTM E1318	<ul style="list-style-type: none"> • Type I, II, III and IV - Type I/II for classification and Type III for enforcement (tolerance: GVW 6%, Wheel load 20%, Axle 15%, Tandem 10%, Speed 1 mph, spacing 0.5 ft. - Type IV for static scale enforcement - 95% compliance 	> See 5.1.
NIST 2.25 (HB44)	<ul style="list-style-type: none"> • Class A (equivalent to Type I) - Tolerance: GVW 10%, Axle 15%, Tandem 20%. Spacing 0.5 ft. - 95% compliance 	> See T.2.
OIML R134-1	<ul style="list-style-type: none"> • More comprehensive Accuracy Class for GVW and Axle - GVW = 0.2, 0.5, 1, 2, 5 and 10 (in % in-service) - Axle Weight for 2-axle calibration truck = A, B, C, D, E, and F for 0.5%, 1.0%, 1.5%, 2.0%, 4.0% and 8.0% - Axle Weight for other calibration trucks = A, B, C, D, E, and F for 1.0%, 2.0%, 3.0%, 3.0% 8.0% and 16.0% - Higher GVW Accuracy will require higher Axle Accuracy. See Table 1 in Section 2.2.1. - 100% compliance 	> See 2.2.1.
COST 323	<ul style="list-style-type: none"> • Class A(5), B+(7), B(10), C(15), D+(20), D(25), E for GVW/Axle - Numbers in the parenthesis denote the GVW accuracy. - B(7) is the minimum requirement for enforcement, and similar to ASTM Type III – GVW 7%, Axle 11%, Tandem 10%, and Wheel Load 14%. - The number denotes the GVW error (%). - Axle error is 35~60% higher than GVW. - 95% compliance 	> See 8.2 (Table 5) & I-5 (Table 12) > See 4.5

Table 5: Accuracy Tolerance Comparison between ASTM E1318, NIST 2.25, OIL-134 and COST

Table 6: Preliminary Comparisons between ASTM E1318, NIST 2.25, OIML-134 and COST 323

Subsection 2.4: Overweight Trucks and Permit

The team reviewed the overweight (OW) and oversize (OS) permit policies of all the states in the US. The permit policies fall into three (3) main fee schedules – (A) flat fee schedule, (B) fee schedule per OW and OS, and (C) fee schedule per OW, OS, and mileage. The permit fee policies were compiled and briefly summarized as below:

Subsection 2.4.1: Flat Fee

- **Arizona:** This state charges a flat OS fee of \$15 and an OW fee of \$75 regardless of size and weight. If the truck is OS and OW, the fee will be added to \$90.
- **California:** Caltrans issues a permit with a flat fee of \$16 for any OS and/or OW.
- **Connecticut:** The state has a \$35 of the flat permit fee for OS and/or OW trucks.
- **Hawaii:** The permit fee varies between \$5 and \$25; however, the HIDOT website does not specify how the fee is determined.
- **Idaho:** The OS fee varies depending on the dimensions (\$28 for typical OS and \$71 for W/H > 16' or L>110'). The OW fee is flat at \$71. The OS/OW truck will need the summation of the typical OS fee and OW fee of \$107.
- **Iowa:** A flat fee of \$10 will be charged to the OS and/or OW permit truck.
- **Kansas:** The fee is \$20 for OS/OW permit truck.
- **Kentucky:** This state charges a flat fee of \$60 per permit truck.
- **Maine:** Similar to Iowa, the permit fee is flat at \$10 per permit.
- **Massachusetts:** The fee schedule is \$40 for any OS and/or OW permit truck.
- **Michigan:** The OS fee is \$15, and the OW or OS/OW fee is \$50.
- **Missouri:** A \$10 flat fee will be charged to the OS/OW permit truck.
- **Montana:** The flat fee is \$10 for OS/OW permit vehicles.
- **Nebraska:** The OS, OW, and OS/OW permit fees are \$15, \$20, and \$25, respectively.
- **Nevada:** The permit fee is \$25.
- **New York:** The permit fee is \$40, but no additional permit is issued, and legacy permits are honored.
- **Oregon:** This state has the lowest permit fee of \$8.5 per permit for OS.
- **South Dakota:** This state charges a flat fee of \$25 regardless of OS and OW.
- **Utah:** The permit fee is \$60, which is valid for 6 months.
- **District of Columbia:** A \$30 fee is required for a single OW permit truck.

Subsection 2.4.2: OS/OW Fee

- **Alabama:** The OS fee is \$10, and the OW fee varies from \$10 and \$100 depending on GVW; \$10 for GVW < 100 kips, \$30 for GVW < 125 kips, \$60 for GVW < 150 kips, and \$100 for GVW > 150 kips.
- **Arkansas:** The OS permit requires \$65 (W/H < 16') or \$75 (W/H > 16'). The OW fee is \$40 for GVW < 150 kips and \$65 for GVW > 150 kips. The OS/OW permit fee varies \$135 ~ \$170 depending on OS and OW.
- **Colorado:** This state charges a flat fee of \$15 for OS. For the case of OS/OW truck, the fee will be \$15 (OS fee) + \$5 per axle.
- **Delaware:** The fee will be \$30 (OS/OW) plus \$10 per every 8 kips of overweight tonnage.
- **Georgia:** The fee is \$30 for GVW 80~150 kips and W/H less than 16', and \$125 for GVW over 150 kips and W/H more than 16'.
- **Maryland:** The OS/OW fee is \$30 plus \$5 per OW tonnage for GVW > 90 kips.
- **New Hampshire:** This state charges \$6 for OS and \$5.5 for OW (GVW less than 130 kips.) The OW permit truck with GVW > 130 kips requires an additional \$1 per every 10 kips of OW and \$2 per every 10 kips of OW if the GVW exceeds 180 kips.
- **New Jersey:** The OS fee is \$10 plus \$1 per foot of each dimension. The OW fee is \$10 plus \$5 per OW tonnage. If the truck is OS/OW, the fee is \$20 plus \$5 per OW tonnage.
- **North Carolina:** There is a \$12 of OS fee per each over-dimension and a \$3 of OW fee per kips for GVW > 132 kips.
- **Oklahoma:** The OS/OW fee is \$40 plus \$10 per kips of OW tonnage.
- **Texas:** The OS or OS/OW basic fee is \$60. Also, various OW fee of \$150, \$225, \$300, or \$410 will be added for GVW > 80 kips, 120 kips, 160 kips, and 200 kips, respectively.
- **Vermont:** This state charges \$28 for OS and \$40 for OW. Besides, a route survey fee is added to any OW (\$800 ~ \$10,000 depending on the total OW).
- **Wisconsin:** The permit requires \$15-\$20 for OS, \$20 for OW, and \$25 for OS/OW plus \$20-\$85 additional fee depending on OW.

Subsection 2.4.3: OS/OW + Mileage Fee

- **Arkansas:** The state charges \$17 for OS/OW per permit truck. An additional \$8, \$10, or \$12 per OW ton will be added depending on the mileages of ~ 100 miles, ~150 miles, and ~ 200 miles, respectively.
- **Florida:** The OS fee varies between \$5 and \$25 depending on the dimensions. The unit OW fee per mileage is determined based on the GVW, which ranges from \$0.27/mile (for GVW 80-95 kips) to \$0.47/mile (for GVW 153-162 kips).

- **Illinois:** The OS fee varies between \$12 and \$125 depending on mileages. The OW fee also varies between \$10 and \$280 depending on mileages and the axle number.
- **Indiana:** This state charges \$20-\$30 of OS/OW fee per dimension, and an OW fee of \$0.35/mile ~ \$1.0/mile is added depending on OW. Also, a \$10 per bridge is added based on the final route.
- **Louisiana:** The OS fee is \$10, and the OW fee is \$30 and up depending on OW, mileage, and axle number.
- **Montana:** The OS/OW fee is \$15, and \$20 per 10 kips of OW tonnage will be added. If the GVW exceeds 160 kips, an analysis fee of \$425 ~ \$925 is added depending on mileages.
- **New Mexico:** The OS/OW permit truck requires to pay \$25 plus \$0.025 per OW ton-mile.
- **North Dakota:** The permit fee consists of \$20 for OS/OW and \$10 per 10 kips for GVW > 150 kips. The maximum permit fee is \$70.
- **Ohio:** The state charges \$75 for OS and \$145 for OS/OW. An OW fee of \$0.04 per kips-mile for GVW > 120 kips is added.
- **Pennsylvania:** The OS fee is \$40, and the OS/OW fee varies between \$36 (W<14') and \$75 (W>14'). An OW fee of \$0.04 per OW ton-mile is added to the OW permit.
- **South Carolina:** The permit fee for OS varies between \$35 and \$50 depending on dimensions. The OW permit fee consists of a basic fee (\$100 ~ \$350 depending on OW), OW fee (\$3/kips for GVW > 130 kips), and mile fee (\$0.05/mile).
- **Tennessee:** The OS fee is \$20-\$30 per dimension. The OW permit fee includes the basic fee of \$20 plus \$0.06/OW ton-mile (GVW < 165 kips) or \$0.12/OW ton-mile (GVW > 165 kips)
- **Virginia:** This state charges \$20 for OS/OW and \$0.3 per mile for any OW permit. An additional fee of \$4 per bridge will be added.
- **Washington:** The OS fee is flat (\$10). The OW fee is \$0.07/mile and up depending on OW tonnage.
- **West Virginia:** The OS/OW fee is \$20, and \$0.04/OW ton-mile is added to the OW permit.
- **Wyoming:** The OS fee is \$25 plus \$0.03/ft of dimension, and the OW fee is \$0.06/ton-mile with a minimum of \$40.

Section 3: Damage Cost due to Paid Single Overweight Trucks

Subsection 3.1: Procedure to Analyze the Permit Data

As New York City and State do not issue any permit based on their weight or size, the team collected the permit data from the New Jersey Department of Transportation (NJDOT) for further analysis from 2013 to 2018. Since the database consists of many tables and many variables that are not relevant to this analysis, the team extracted three tables (TripRequest, LinkPerRequest, and Vehicle) to establish a new database containing essential variables to perform the analysis. TripRequest table includes the permit properties, such as fees, permit date, permit type, etc. LinkPerRequest table includes all the links

between mileposts that each permit vehicle will pass. The Vehicle table includes the gross vehicle weight (GVW), axle weight, axle spacing, etc. to distinguish the vehicle configuration. Figure 2 shows the structure of the NJDOT permit database.

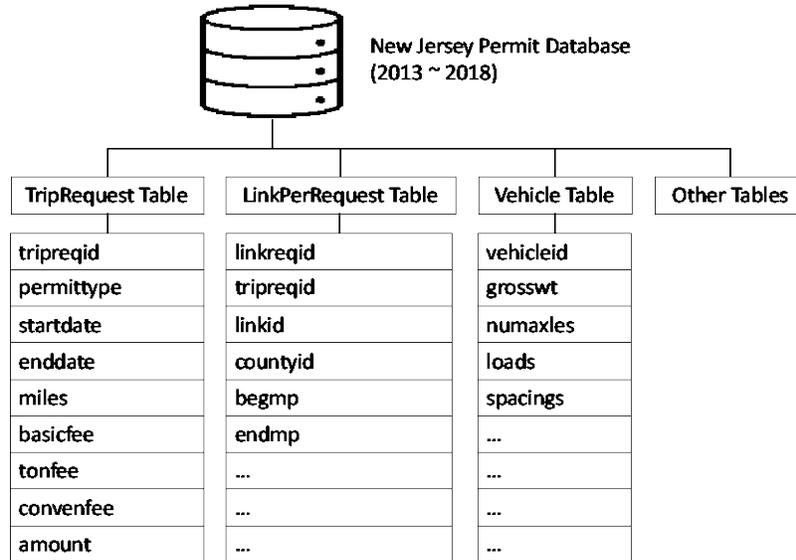


Figure 2: NJDOT Permit Database

The team developed a web-based application that can visualize the permit records as well as estimate the damage cost incurred on the infrastructure due to these overweight trucks (Nassif et al., 2019). Many programming languages were used in the development of this tool, including JavaScript, MySQL, MSSQL, PHP, and C++. Moreover, the Application Programming Interface (API) of Google Maps was utilized for mapping the links on the interface. The architecture of the tool followed the general client (front-end) – server (back-end) model. The client interface was designed to be user-friendly for easily querying the parts of the infrastructure using a GIS map. All calculations in the tool were performed at a server by sending AJAX requests to the server to minimize the dependency on the client resources. The asynchronous requests are made to send and receive data from the server without refreshing the user interface. Figure 3 shows the screenshot of this web-based application.

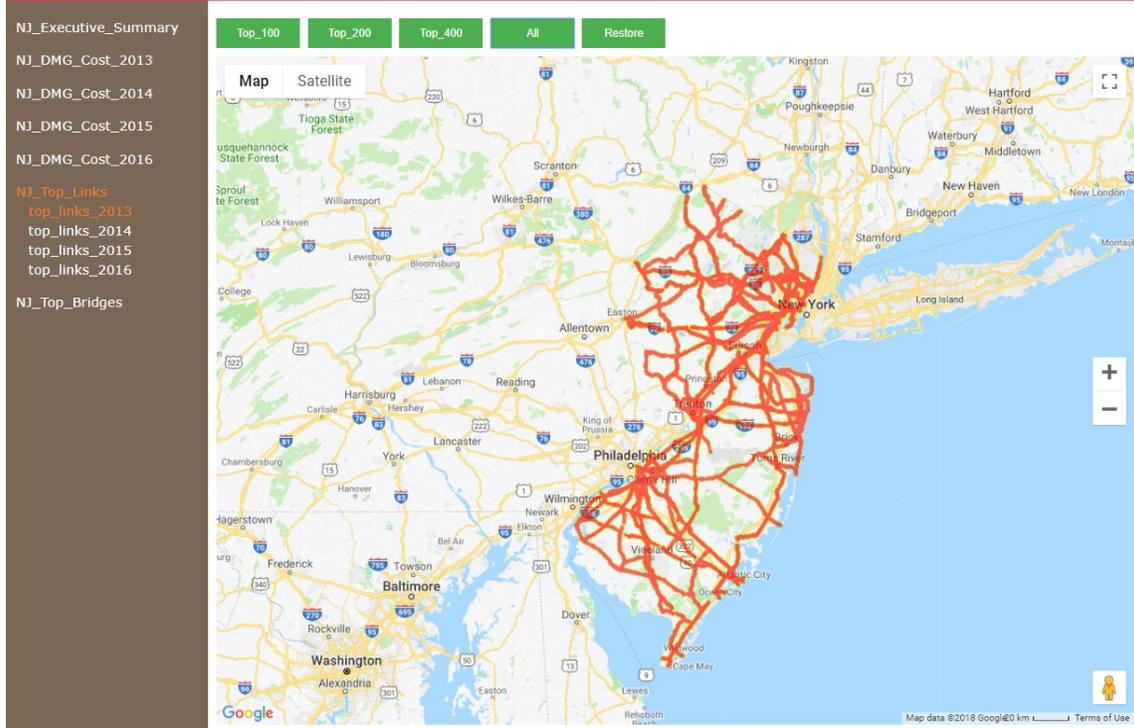


Figure 3: Interface of the Tool Displaying NJ Roadway Network

For the calculations in the tool, infrastructure data from the following sources were also fused to the unified database:

- The NJ Straight Line Diagrams (SLD) were utilized to generate a geographic layer where the links on the NJ roadway network displayed using GoogleMaps API.
- The National Bridge Inventory (NBI) data provided the properties and locations of all the bridges maintained by NJDOT, which was required as input for the bridge deterioration models.

Figure 4 shows how the permit route is selected. The permit route will be a combination of the shortest links between two mileposts excluding various constraints, such as low bridge clearance, bridge under construction, local road, etc. However, this does not guarantee the shortest distance because of various constraints. In each link, the pavement type, bridge type, and the number of bridges will be selected to estimate the infrastructure damage cost due to a single trip permit vehicle. The total damage cost is the summation of the pavement damage cost (depending on the pavement type) and bridge damage cost (depending on the bridge type and size) for each link on the permit truck’s trip path.

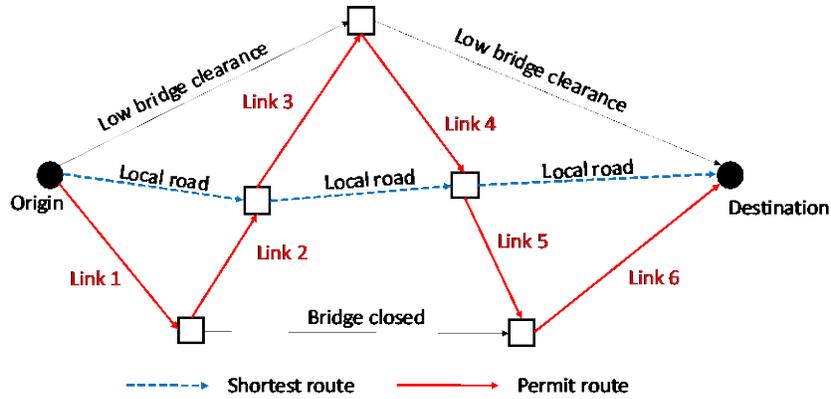


Figure 4: Permit Route for the Estimation of the Link Level Permit Damage Costs

Subsection 3.2 Damage Cost Components

Subsection 3.2.1: Pavement Damage Cost

The pavement damage was calculated using the following Eq. (8) developed in the previous study (Nassif et al., 2015).

$$\text{Pavement Damage Cost (PDC)} = \text{ESAL} \times \text{UPC} \times \text{Miles} \times \text{Lane} \quad (\text{Eq. 8})$$

where ESAL = Equivalent Single Axle Load (1/kips)

UPC = Unit Pavement Cost (\$/ESAL/mile/lane)

Lane = Number of Lanes

For simplicity in the unit pavement cost, the team assumed a thick pavement for the interstate and US routes and a thin pavement for other routes. ESAL value required in pavement damage calculations was estimated using ESAL equations from the previous study along with the axle loads and spacings of the vehicles (Nassif et al., 2015).

Analysis Period	Road Category	Average	Range
30 Year	Interstate highway	0.038	0.027 – 0.052
	State road	0.250	0.092 – 0.483

Table 7: Proposed Pavement Damage Cost for New Jersey, \$/ESAL/lanes/miles (Nassif et al., 2015)

Subsection 3.2.2: Bridge Damage Cost

For the estimation of the bridge damage cost, the deterioration models developed in the former study were utilized (Nassif et al., 2015). Accordingly, the following Eq. (9) was used for estimating the bridge damage cost:

$$\text{Bridge Damage Cost (BDC)} = \text{UBC} \times \text{Area} \times \text{GVW} \quad (\text{Eq. 9})$$

where UBC = Unit Bridge Cost (\$/kips-ft²)

GVW = Gross Vehicle Weight of Permit Vehicle (kips)

Area = Total Square Footage of the Bridge(ft²)

The unit deck and girder damage costs based on bridge type and road type were estimated in the former study that calculated unit costs for the whole truck population and only overweight (OW) trucks, separately. Since this study solely focuses on overweight trucks, the overweight unit costs were used, as shown in Table 8. In this table, the girder cost is divided into four categories depending on the girder materials and girder arrangements: (a) steel multi-girder, (b) steel floorbeam girder, (c) prestressed concrete (PSC) girder, and (d) other materials. The unit bridge damage costs on different road types indicated that more considerable damage was incurred on the bridges on the state routes than the interstate roadways for the same loads. This is because the bridges on the state roads are not designed to carry heavier loads. Unlike the unit pavement damage costs, the unit bridge damage cost is independent of ESAL; however, it is correlated to the vehicle's GVW. Hence, according to these deterioration models, the pavement damage can be decreased for a given permit truck by re-distributing the weight; on the other hand, the bridge damage would remain the same as the GVW governs it.

Bridge Type	Road Type	Unit Bridge Damage Cost (\$/kips/ft ²)	Typical Bridge Damage Cost for a Deck 40 ft x 200 ft and for 10 kips OW
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Bridge Deck		Interstate	$\$3.2 \times 10^{-6}$	25.6 cents
		US Hwy	$\$2.7 \times 10^{-6}$	21.6 cents
		NJ Hwy	$\$4.1 \times 10^{-6}$	32.8 cents
Girder	Steel Multi Girder	Interstate	$\$4.1 \times 10^{-7}$	3.3 cents
		US Hwy	$\$3.5 \times 10^{-7}$	2.8 cents
		NJ Hwy	$\$4.3 \times 10^{-7}$	3.4 cents
	Steel Floorbeam Girder	Interstate	$\$5.9 \times 10^{-7}$	4.7 cents
		US Hwy	$\$3.9 \times 10^{-7}$	3.1 cents
		NJ Hwy	$\$4.7 \times 10^{-7}$	3.8 cents
	PSC Girder	Interstate	$\$2.1 \times 10^{-7}$	1.7 cents
		US Hwy	$\$2.9 \times 10^{-7}$	2.3 cents
		NJ Hwy	$\$3.7 \times 10^{-7}$	3.0 cents
	Other Materials Girder	Interstate	$\$3.1 \times 10^{-7}$	2.5 cents
		US Hwy	$\$3.2 \times 10^{-7}$	2.6 cents
		NJ Hwy	$\$4.0 \times 10^{-7}$	3.2 cents

Table 8: Unit Bridge Damage Cost by Bridge and Roadway Type (Nassif et al., 2015)

Subsection 3.3: Overweight Permit Trends over Time

The permit records from 2013 to 2018 in three main tables (Vehicle table: 880,538, TripRequest table: 864,498, and LinkPerRequest table: 53,556,373) were used for this analysis. Figure 5 shows the GVW distribution of all the permit vehicles from 2013 to 2018 (Vehicle table) that exceeded the GVW of 80 kips. The majority of permit vehicle in the database (over 90%) was below 150 kips, and the median GVW value fell between 110 kips and 120 kips of GVW. The average GVW was found to be 121 kips.

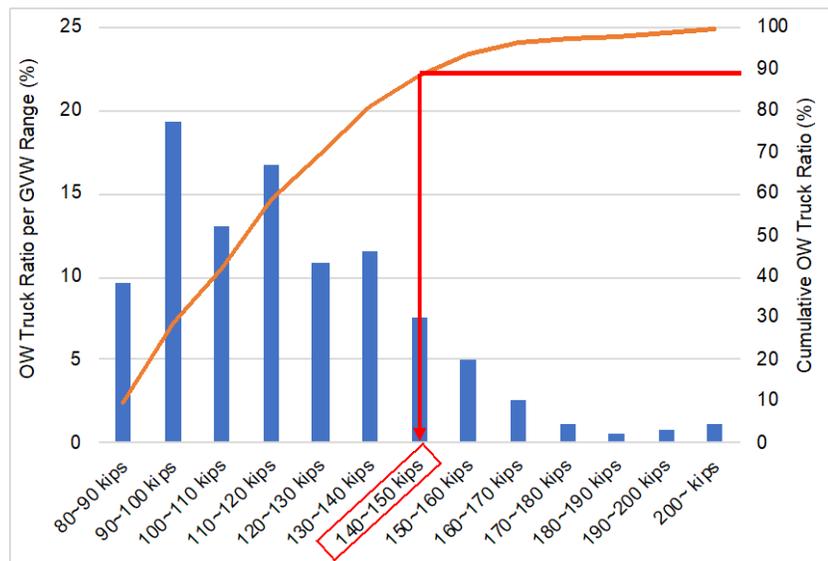


Figure 5: Percentage Distribution of Permit Vehicles

Subsection 3.3.1: Number of Overweight Permit Vehicles

The complete permit database included 630,023 records. The data consists of different types of NJ permits; (1) single trip permit, (2) Code 23 registration, (3) Ocean-Borne permit, and (4) other permit. Single trip permit consists of oversized (OS), overweight (OW), and OS/OW permits, and all require a fixed administrative fee of \$12.6. OS truck will pay an additional fee for any oversized dimension, while the OW truck will pay an additional fee for an overweight tonnage fee above 80 kips. Code 23 registration is issued to the trailer every year. The trailer with Code 23 registration can carry OS/OW load for a single trip, and it requires a fixed administrative fee of \$12.6 regardless of oversized and overweight. The ocean-Borne permit is given to the truck to carry a divisible load, and no permit fee is collected. Other permits are issued to OS/OW vehicles owned by FHWA or the military without any fee.

Table 9 shows the number of records in these permit categories for the analysis period. The number of OW permits (single OW/OS permit with overweight tonnage fee, single OW/OS permit with Code 23

registration, and other permits) accounted for approximately 53% of all permits. Moreover, among the single trip OW/OS permits, approx. 46% of OW permits were single trip OW permit with paid overweight tonnage fee, while the rest (54%) was comprised of single trip OW/OS permits with Code 23 registration, Ocean-Borne permits, and EVs.

Year	(1) All Permit (OW/OS)	Single Trip Permits (with OW tonnage fee)		Single Trip Permits (with Code 23 registration) ³		Others (Ocean-Borne & EV) ⁴
		(2) OW/OS ¹	(3) OS ²	(4) OW/OS	(5) OS	(6) OW
2013	96,534	21,498	45,153	20,538	4,035	5,310
2014	102,287	23,006	48,819	21,092	3,966	5,404
2015	103,347	23,996	47,071	23,539	3,051	5,690
2016	108,420	26,529	45,344	27,455	2,321	6,771
2017	111,975	28,378	46,685	26,733	2,589	7,590
2018	107,460	28,930	45,177	23,874	2,747	6,732
Total	630,023	152,337	278,249	143,231	18,709	37,497
Avg.	105,004	25,390	46,375	23,872	3,118	6,250
Ratio	100%	24%	44%	23%	3%	6%
Remarks	¹ OS + OW Fee ² OS Fee ³ No OS or OW fee will be charged, but only the fixed administrative fee of \$12.6 will be applied. ⁴ OW but no fee (\$0).					

Table 9: OW Permit Frequency by Category in 2011-2018

The trend in the number of permits issued over the years can be observed in Figure 6. In this figure, “All Permits” refers to (1) of Table 9 which includes all permit types, “OW Permits” represents the summation of (2), (4), and (6) of Table 9 which includes all OW permits regardless of OW tonnage fee, and “Single OW Permits with OW Tonnage Fee” refers to (2) of Table 9 that pay the overweight tonnage fee for all GVW over 80 kips. Figure 6 shows that the number of “All Permits” issued increased by 12.1% annually, whereas the “OW Permits” and “Single OW Permits with OW Tonnage Fee” increased at a rate of 7.1% and 3.8%, respectively.

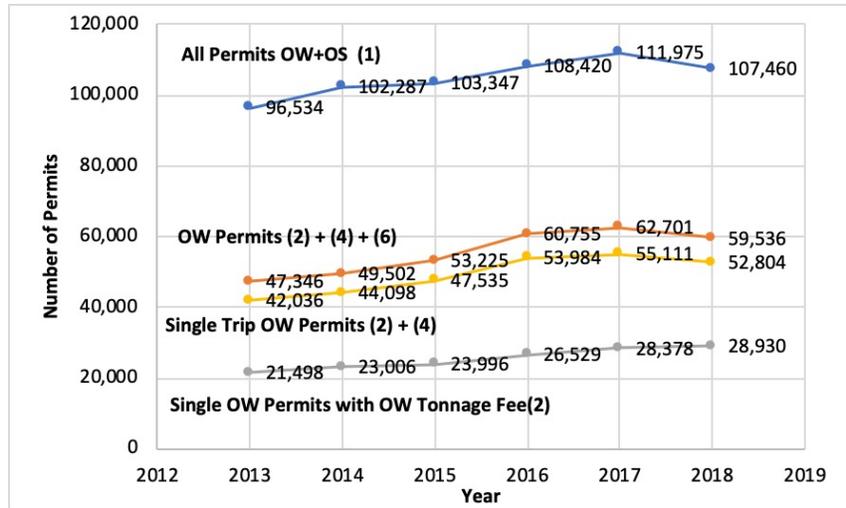


Figure 6: Number of Permit Trucks over Years (2013-2018)

Subsection 3.4: Impact of Permit Trucks on the Infrastructure

The bridge and pavement damage costs due to single OW permits (both OW tonnage fee and Code 23 registration) were calculated for each single OW permit based on Eq. (8) and Eq. (9). Only single OW permits were considered for this estimation because these permit records provide the route with an origin, destination, and mileposts, which are the essential information to calculate the infrastructure damage. The results are summarized in Figure 7. The pavement damage varies from \$2.2 million to \$3.5 million per year, and the average pavement damage is approximately \$2.8 million per year. Figure 7 presents the bar chart for the collected OW tonnage fee and the damage fee. It shows that the pavement damage was predominant and almost two times higher than the bridge damage. The pavement and bridge damages were 62.7% and 37.3% of total damage, respectively.

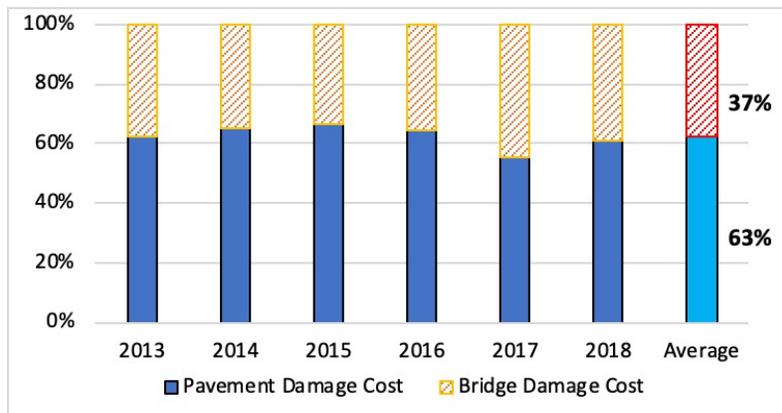


Figure 7: Infrastructure Damage Cost due to Single OW Permits

Table 10 summarizes the total estimated infrastructure damage cost due to the single trip OW permits (with OW tonnage fee and Code 23 registration) as well as collected OW tonnage fees for single trip OW trucks. The average estimated damage cost due to all single trip OW permits was \$4,568,102 per year. The single trip OW permits with OW tonnage fee contributed 55% of this damage (\$2,530,635), and the single trip OW permits with Code 23 registration contributed 45% of the total damage cost. However, the collected OW tonnage fee of the single trip permits was \$2,105,112 on average, covering 46% of estimated damage due to all single trip OW permits or 83% of damage due to single trip OW permits with OW tonnage fee. The results show that the current NJ permit system recovers most of the infrastructure damage (83%) from the collected OW tonnage fees. However, the single trip OW permits with Code 23 registration would not contribute to any revenue that could maintain the infrastructure damages.

Year	(A) Collected OW Tonnage Fee for Single Trip OW Permits (2) in Table 9	Total Estimated Damage Cost (Pavement + Bridge)		
		(B) All Single Trip OW Permits (2) + (4) in Table 9	(C) Single Trip OW Permits with OW Tonnage Fee (2) in Table 9	(D) Single Trip OW Permits with Code 23 Registration (4) in Table 9
2013	\$1,842,500	\$3,611,636	\$1,944,845	\$1,666,791
2014	\$1,903,905	\$4,122,809	\$2,316,187	\$1,806,621
2015	\$2,047,151	\$4,872,564	\$2,927,491	\$1,945,072
2016	\$2,211,364	\$5,525,039	\$3,316,982	\$2,208,057
2017	\$2,321,367	\$4,823,001	\$2,360,062	\$2,462,939
2018	\$2,304,382	\$4,453,564	\$2,318,240	\$2,135,323
Average	\$2,105,112	\$4,568,102	\$2,530,635	\$2,037,467
Remarks	46% of (B) 83% of (C)	-	55% of (B)	45% of (B)

Table 10: Damage Cost and Paid OW Tonnage Fee

Subsection 3.5: Use of WIM Data to Back-trace Permit Routes

So far, we learned that the permit trucks impose considerable damage to the infrastructure. Hence, it is crucial to determine the more impacted areas on the infrastructure. Further, it is vital to identify the individual violators since it was proven the infrastructure might suffer substantially from an illegal overweight truck, which might even lead to total failure of a bridge such as the I-35W Mississippi River bridge collapse in Washington state. Overweight permits enable officials to examine and to impose a specific route for the overweight trucks. In contrast, initial checks might be performed on the route-based weight limits and dimensions of the bridges on the proposed route. It is not possible to know if these trucks follow the route assigned to them. This requires a tracking mechanism. While RFID devices can be used for this purpose, a network of RFID readers to track RFID sensors, for solely tracking, can be very costly. Another way to geo-fence the permit routes can be accomplished using the existing WIM sensors. Some states, such as New Jersey, have a well-established WIM network consisting of more than eighty sites throughout the state. These WIM sensors can detect overweight vehicles and their configuration. As discussed, the routes of the permit vehicles in NJ are also known, by matching the links on the permit route to the WIM locations, it is possible to get a general idea about where the overweight trucks, containing both permitted and illegal vehicles, are traveling to (Figure 8). However, to be able to back-trace individual permit vehicles, they need to be identified by means of a secondary technology, such as cameras, that is integrated into the WIM system. This would make it possible to identify each overweight vehicle regardless of being permitted or illegal. Consequently, this could enable the permit route's enforcement by examining if the WIM link was in the reported permit route (geo-fencing). Such an integrated system can also detect the weight limit violators and can facilitate weight enforcement.

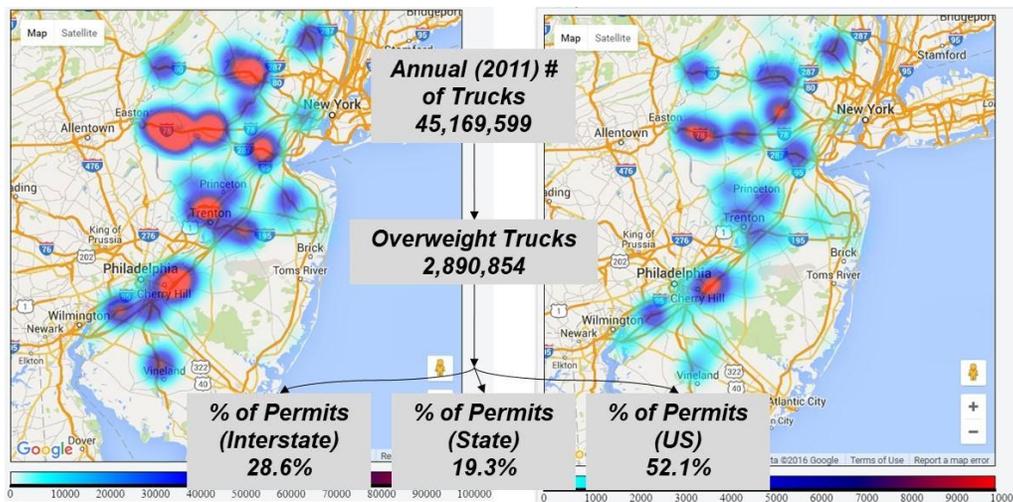


Figure 8: Heatmap of (a) the OW trucks from WIM data and (b) the coinciding permit links

Section 4: Permit Fee Policy

As described in Section 2.5, the permit fee policies for all 50 states and the District of Columbia (D.C) were reviewed. Each state has its own permit fee policy to encourage the goods and services to be distributed across the states and between states. In general, the permit fee schedule consists of three categories: (1) flat fee, (2) oversized (OS) fee, and overweight (OW) fee, and (3) OS/OW fee plus mileage fee. Table 11 summarizes the number of states and states abbreviations for three fee schedule categories. This information is schematized in a different color in Figure 9. Most west states (61%) adopt the flat fee for all permits regardless of overweight or oversized. Most mid-west regions adopt the flat fee (42%) and OS/OW + mileage fees (50%). For the south region, OS/OW permits are the majority (88%) with and without mileage. In the case of the east region, 5 states (including NY) adopt the flat fee (56%), 3 states (including NJ) adopt the OS/OW fee (33%), and one state (PA) adopts the OS/OW + mileage fee (11%).

Fee Schedule	No. of States	West (AK/HI)	Mid-West	South	Northeast
Flat Fee	21	OR, ID, MT, CA, NV, UT, AZ, HI (8)	SD, NE, KS, IA, MI (5)	KY, MS, D.C. (3)	NY, CT, MA, RI, ME (5)
OS/OW Fee	13	AK, CO (2)	WI (1)	TX, OK, AL, GA, NC, MD, DE (7)	NJ, VT, NH (3)
OS/OW +Milage Fee	17	WA, WY, NM (3)	ND, MN, MO, IL, IN, OH (6)	AR, LA, TN, VA, WV, SC, FL (7)	PA (1)

Total	51	13	12	17	9
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Table 11: Overweight and Oversize Permit Schedule Summary

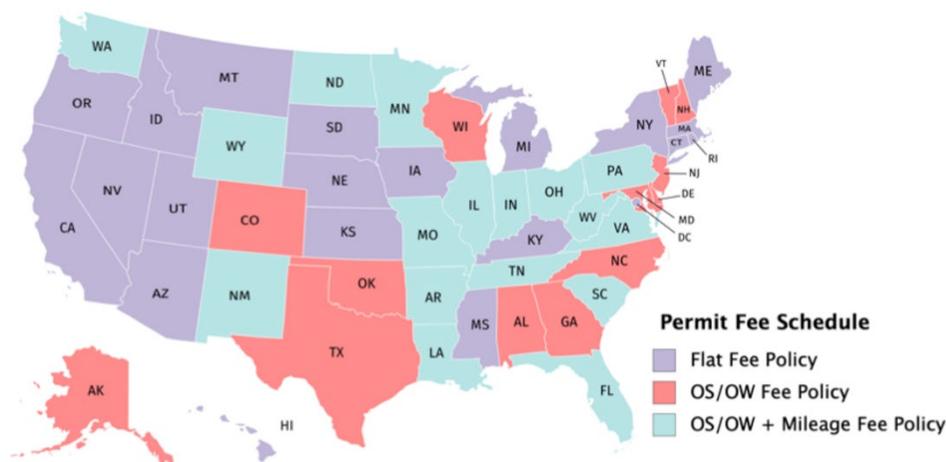


Figure 9: Permit Schedule Map per State

Subsection 4.1: Flat Fee States

Local Department of Transportations in 21 states in the U.S. regulate the permit per flat fee basis (see Figure 10). The fees generally include the base permit fee for either oversize or overweight or both oversize and overweight, which varies between \$5 and \$107. Oregon State has the lowest OS/OW permit fee of \$8.5 per single permit, while Idaho state has the highest OS/OW permit fee of \$107. The state of Hawaii has a variable OS/OW permit fee ranging from \$5 to \$25, but the Hawaii DOT does not describe how the actual permit fee is determined within that range. The permit fees in the flat fee states range from \$10 to \$40, and the average flat permit fee among these states is \$31 (see Figure 11).

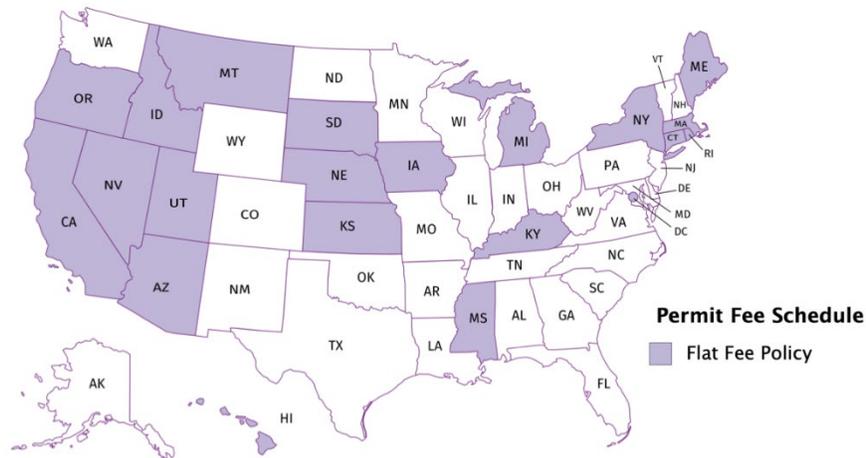


Figure 10: Flat Permit Fee Schedule Map

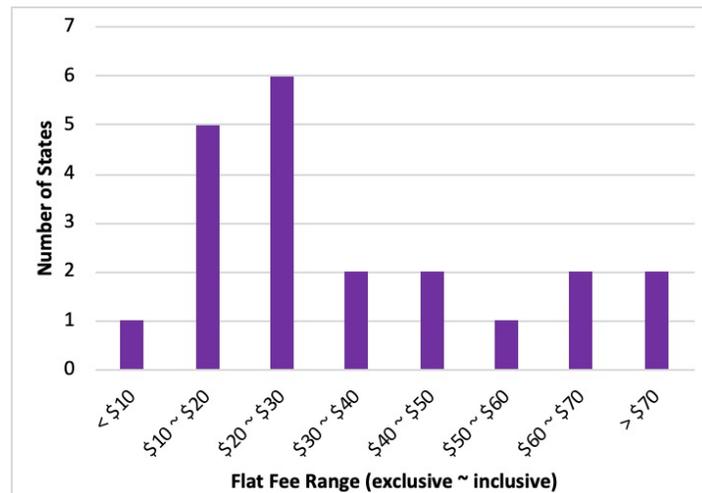


Figure 11: Flat Permit Fee Histogram

Subsection 4.2: OS/OW States

New Jersey is one of the states that adopt the permit fee per oversize (OS) and overweight (OW). For the OS permit, 8 states charge a flat fee for OS permits (Alabama, Colorado, Delaware, Maryland, New Hampshire, Oklahoma, Texas, and Vermont). In comparison, 5 states charge a variable fee for an OS permit depending on the extent of OS (Alaska, Georgia, New Jersey, North Carolina, and Wisconsin), as shown in Figure 12. In the case of the flat OS permit fee, the minimum fee for OS permit is \$6 (New Hampshire), and the maximum is \$60 (Texas). The average flat OS permit fee is \$27 among 8 states. The OS permit fee for New Jersey consists of \$10 of the base fee plus \$1 per foot of any oversize. Similarly, the OS permit fee for North Carolina is \$12 per each oversize (either width, height or length).

For a given OS truck with 16' wide, 16' high, and 70' long, the minimum OS permit fee is \$6 (Oklahoma), the maximum fee is \$65 (Alaska), and the average OS fee is \$30 (see Figure 13). The OS permit fee for New Jersey is \$33, which is just above the average OS permit fee.

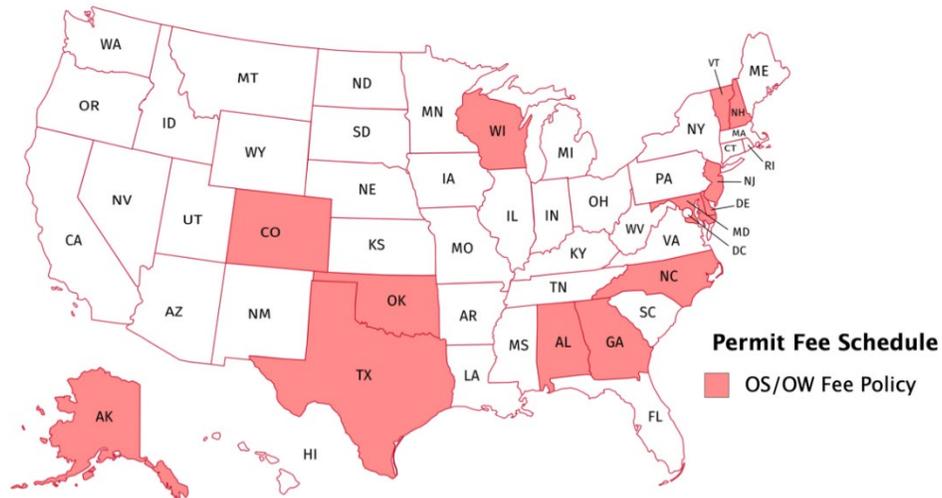


Figure 12: OS/OW Permit Schedule Map

For the OW permit, 4 states charge a variable fee from the OW permits based on the overweight range (Alabama, Alaska, Georgia, and Texas), 6 states charge a fee based on the overweight tonnage (Delaware, Maryland, New Hampshire, New Jersey, North Carolina, and Oklahoma), 2 states charge a flat OW fee (Alaska and Vermont), and one state provides the OW permit based on the number of axles (Colorado). It is worth noting that, in addition to the OW permit fee, Vermont also requires a route survey fee that varies between \$800 (for 80-150 kips of GVW) and \$10,000 (for 250+ kips of GVW). However, this route survey fee should not be included in the permit fee as it is an additional cost to the submitter for the engineering survey to obtain the permit. Among all states, for a given OW truck (GVW = 150 kips with 7 axles), the minimum OW permit fee is charged in New Hampshire (\$6.5), the maximum is charged in Oklahoma (\$540), and the average OW permit fee is calculated as \$119 (see Figure 14). It should be noted that for that truck, New Jersey charges \$154, which is significantly above the average for the US.

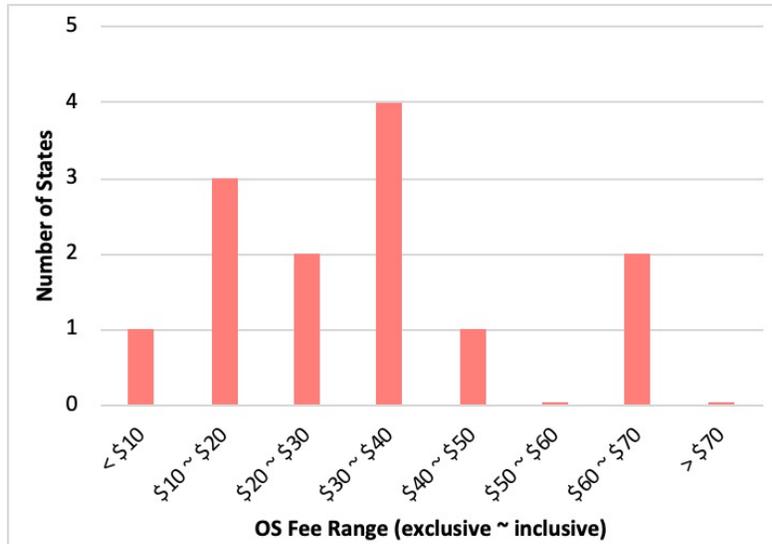


Figure 13: OS Permit Fee Histogram

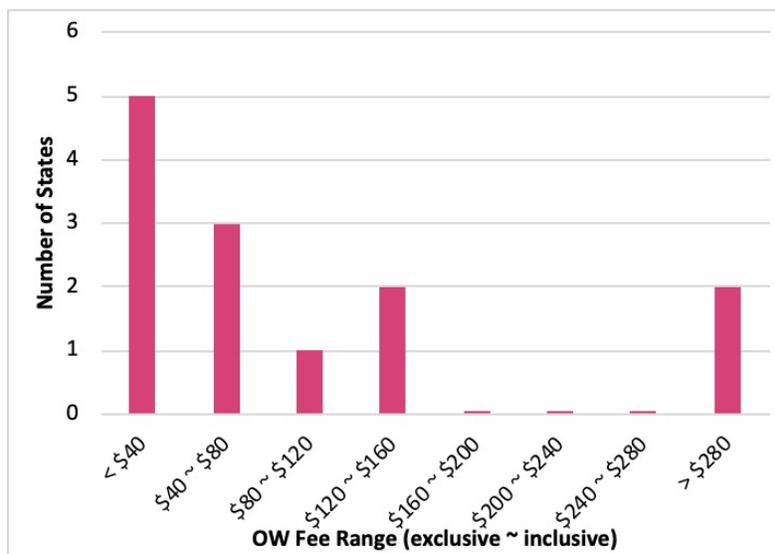


Figure 14: OW Permit Fee Histogram

Subsection 4.3: OS/OW/Mileage States

Seventeen states issue a permit based on OS, OW, and mileage, as shown in Figure 15. Among these states, there are 4 different fee schedules, as summarized in Table 12.

- \$/OW depending on mileage: The unit fee per OW (either ton or kips) is increased for higher mileage. In the case of AR, the unit fee is \$8/OW tonnage for the mileage between 1-100 miles, \$10 for 101-150 miles, and \$12 for 151-200 miles.
- \$/mile depending on OW: The unit fee per mile increases for heavier trucks. In FL, the unit fee is \$0.27/mile for GVW of 80-95 kips, \$0.32/mile for GVW of 95-112 kips, and so on.
- \$/OW-mile: The unit fee is fixed for each OW and mileage. For example, West Virginia charges \$0.04 per OW tonnage and mile.
- \$ depending on OW and mileage: The fee is fixed depending on OW and mileage range. In the case of LA, the unit fee varies, such as, \$30 for GVW of 80-100 kips with 50-100 miles, \$45 for GVW of 80-100 kips with 51-100 miles, and so on.

Also, two states (IN and VA) charges a bridge analysis fee per bridge, while MO charges the variable analysis fee depending on mileage. IL accounts for the number of axles to estimate the permit fee.

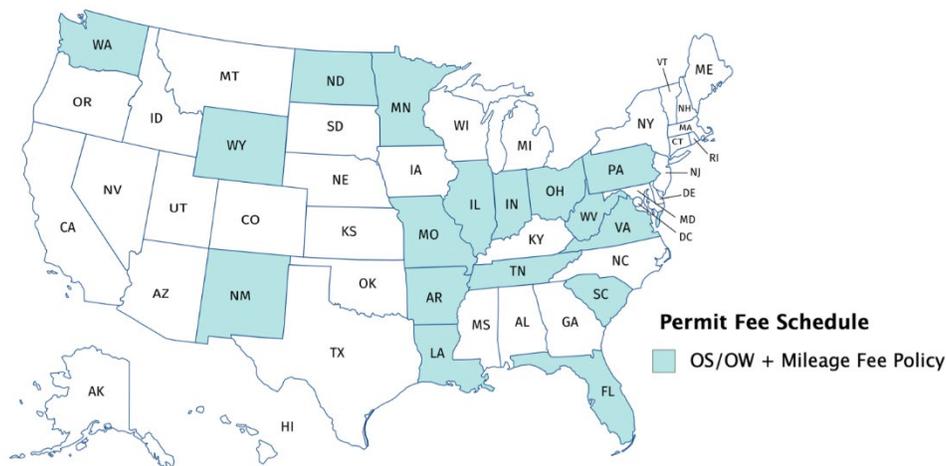


Figure 15: OS/OW/Mileage Permit Schedule Map

State	Basic Fee Schedule
AR	\$/OW depending on mile
FL	\$/mile depending on OW
IL	\$ depending on OW and mile + number of axle
IN	\$/mile depending on OW
LA	\$ depending on OW and mile
MO	\$/OW + engineering analysis fee (\$) depending on mile range
NM	\$/OW-mile
OH	\$/OW-mile
PA	\$/OW-mile
SC	\$/OW plus fixed \$/mile + Engineering analysis fee for GVW > 130 kips
TN	\$/OW-mile
VA	\$/mile + \$4/bridge
WA	\$/mile depending on OW
WV	\$/OW-mile
WY	\$/OW-mile

Table 12: Fee Schedule for OS/OW/Mileage States

Subsection 4.4: National Permit Fee Analysis based on NJ Permit Data

The team utilized the permit data obtained from NJDOT and applied the permit data to permit schedules of all states and D.C. (except Minnesota) to estimate the average permit fee per vehicle across the U.S. In the case of the flat fee, the permit fee remained the same between \$8.5 (Oregon) and \$107 (Idaho). For the weight-based permit fees, 4 states charge a variable fee from the OW permits based on the OW range (Alabama, Alaska, Georgia, and Texas), 6 states charge a fee based on the OW tonnage (Delaware, Maryland, New Hampshire, New Jersey, North Carolina, and Oklahoma), 2 states charge a flat OW fee (Alaska and Vermont), and one state provides the OW permit based on the number of axles (Colorado). Any engineering fee was not included in this analysis because it would guide a wrong conclusion. Figure 16 shows the number of states per each average permit fee range and Figure 17 shows the heatmap of the average permit fee. Figure 16 and Figure 17 have the same color codes: the dark red means more expensive and the light orange means less expensive. The average permit fee using NJ permit record is \$45 per truck. The flat fee is the lowest (\$32) and OS/OW fee without mileage is the highest (\$79). The west, mid-west and northeast regions have similar average permit fee between \$42 and \$49, while the average permit fee for the south region has the most expensive permit fee of \$76.

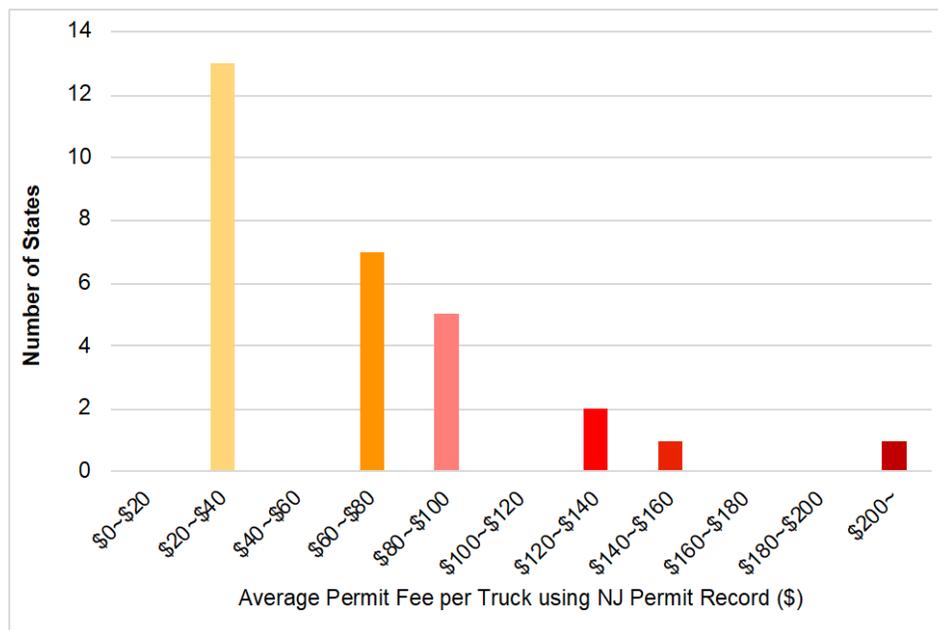


Figure 16: Average OW Permit Fee Paid by a Truck using NJ Permit Data

Section 5: Methodology to Improve WIM Data Accuracy

As PVDF sensors are susceptible to temperature variation, the effects of temperature on weight measurement should be considered to provide reliable WIM data. The calibration test using a calibration truck with known weight would be a good procedure to cover different temperature ranges for accurate weight measurement. However, it would be feasible to cover all temperature ranges over the years and using the results from calibrations performed during summer would not help to adjust WIM data recorded during winter. Therefore, it is important to develop a methodology to update the WIM data per pavement temperature.

Subsection 5.1: Procedure to Update WIM Data per FAW

An approach to minimize the error of WIM data based on the correlation between ambient and pavement temperature is presented. The approach uses the model proposed by Diefenderfer et al. (2006) to correlate the maximum and minimum ambient temperature with those pavement temperatures. The method is developed mainly to PVDF sensors but could be applied to other kinds of piezoelectric sensors. A sample of data ranging from March 2016 to August 2016 is used for this analysis.

A reliable approach to compute correction factors to compensate for the effect of temperature on the WIM system is to use the FAW of Class 9 trucks, also known as 3S2, Type with a 3-axle tractor and a 2-axle trailer. This type of truck is the most frequent commercial truck on US highways. In general, the weight of the semi-trailer is only distributed to tractor tandem. Therefore, the FAW or steering axle weight is almost independent of the weight of the semi-trailer. The national average FAW for the mid-range of GVW (40-80 kips) is 11.7 kips, regardless of the GVW (Nichols et al., 2015). This characteristic allows engineers to use this type of truck to correct WIM data when the pavement temperature data is also available. If a correlation between FAW and pavement temperature is built, an adjustment could be made so that the mean value of FAW of Class 9 trucks for each pavement temperature coincides with a horizontal line over the value 11.7 kips.

Additionally, after performing this temperature compensation, the results would be verified by Southgate's method (2001). This method is based on an extensive database of past results and physical characteristics of trucks, as described earlier. Southgate (2001) used a logarithmic regression of axle spacing and weight to check WIM data. The procedure is applied to Class 9 Trucks once, as mentioned early, the FAW properties are only related to the drive tractor, not the total load of the truck. Further, Class 9 Trucks are the same used by most WIM systems for auto-calibration. The LTPP data also provides the trend between the FAW and the GVW (Chou et al., 2016). It shows that the FAW increases up to 10.7 kips as the GVW increases up to 40 kips at 1.9 kips of FAW per 10 kips of GVW. When the GVW exceeds 40 kips, the FAW change reduces to a lower rate of 0.3 kips of FAW per 10 kips of GVW.

The average FAW is approx. 11.7 kips in the ranges between 10.7 kips and 13.5 kips for the GVW ranges between 40 kips and 120 kips. Finally, the correction factors are then applied to the whole sample of WIM data.

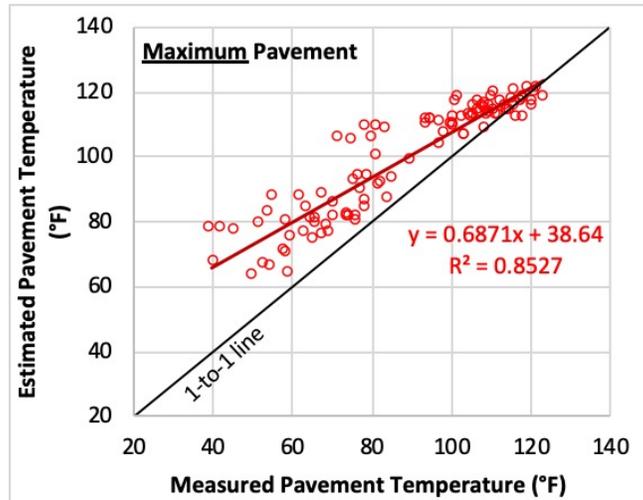
A general approach to estimate the pavement temperature from ambient temperature and to compensate for the temperature effect for minimizing the WIM data error is presented as follow:

- i) Gather the maximum and minimum ambient temperature for each day;
- ii) Estimate the maximum and minimum pavement temperature for each day using Eq. (6) to (7), respectively;
- iii) By linear interpolation, with the hourly ambient temperature, find the pavement temperatures for each hour within each day;
- iv) Cluster and average the FAW of the trucks by intervals of 5°F;
- v) Establish the correlation between FAW and estimated pavement temperature and use regression to adjust the FAW to a horizontal line over the 11.7 kips value;
- vi) Use the test proposed by Southgate (2001) to check the quality of the adjustment;
- vii) Apply the correction factors to the whole sample of WIM data;

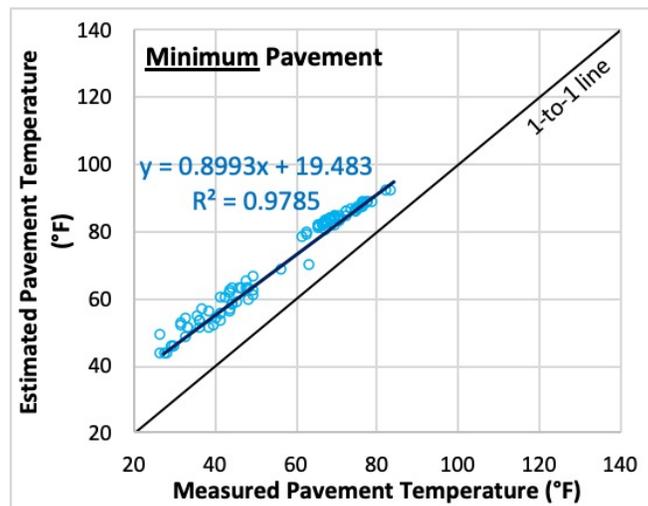
Subsection 5.2: Estimation of Pavement Temperature

Figure 18(a) shows the maximum estimated pavement temperature from Eq. (6) versus the measured pavement temperature at 3/4 in. (20 mm) depth of the pavement. Figure 18(b) explains the minimum pavement temperature from Eq. (7) versus the measured pavement temperature. The proposed equations for maximum and minimum pavement temperatures provide a relationship close to one-to-one between estimated and measured pavement temperatures (Diefenderfer et al., 2006). The coefficient of determination (R^2) of maximum temperature (0.85275) is lower than that of minimum temperature (0.97852). The minimum temperature can be more accurately estimated than the maximum temperature because the thermodynamic properties such as thermal radiation and absorption may play an essential role in the maximum temperature. The estimated pavement temperatures were slightly biased to be higher than the actual pavement temperature.

The pavement temperature per hour was then estimated by linear interpolation between estimated maximum and minimum pavement temperatures (see Eq. (6) and Eq. (7)) and maximum and minimum ambient temperatures. For example, when the maximum and minimum ambient temperatures are 90°F and 70°F, respectively, the maximum and minimum estimated pavement temperatures would be 100°F and 64°F, respectively. In this case, if the ambient temperature is 80°F, the estimated pavement temperature would be 82°F.



(a)



(b)

Figure 18: Measured vs. Estimated Daily Pavement Temperature; (a) Maximum and (b) Minimum

The WIM data for 108 days were re-calibrated by the measured and estimated pavement temperatures. First, it is assumed that the FAW of Class 9 Truck will be 11.7 kips, regardless of GVW (Chou et al., 2016). If the temperature effect is not compensated in the WIM data, the FAW varies depending on the pavement temperature as the PVDF sensor is susceptible to distortions by the temperature variations. It

is assumed that the FAW error will be a linear relationship per lane throughout the temperature ranges observed in the field. The pavement temperature effect on FAW was compensated so that the average FAW of Class 9 Truck will be 11.7 kips regardless of pavement temperature. Figure 19 shows the raw FAW without any temperature correction and corrected FAW per each 5°F of pavement temperature using the measured and estimated pavement temperature. The mean FAW of Class 9 Truck within 5°F of pavement temperature was taken as one value to represent the FAW at each temperature range. “Corrected FAW by Calibration Test” results from the calibration test performed at the temperature ranges between 20°F and 50°F. When the same pavement temperature range (20~50°F) is examined in Figure 19, the corrected mean FAW varies between 10.5 kips and 12 kips and is very close to 11.7 kips. However, when the pavement temperature exceeds this range, the FAW exceeds 11.7 kips and increases up to 16.3 kips. This means that a one-day calibration test at a small temperature range would not be enough to correct the WIM data. Thus, multiple calibration tests during different seasons are necessary to cover the wide range of pavement temperature and, therefore, to improve the accuracy of WIM data.

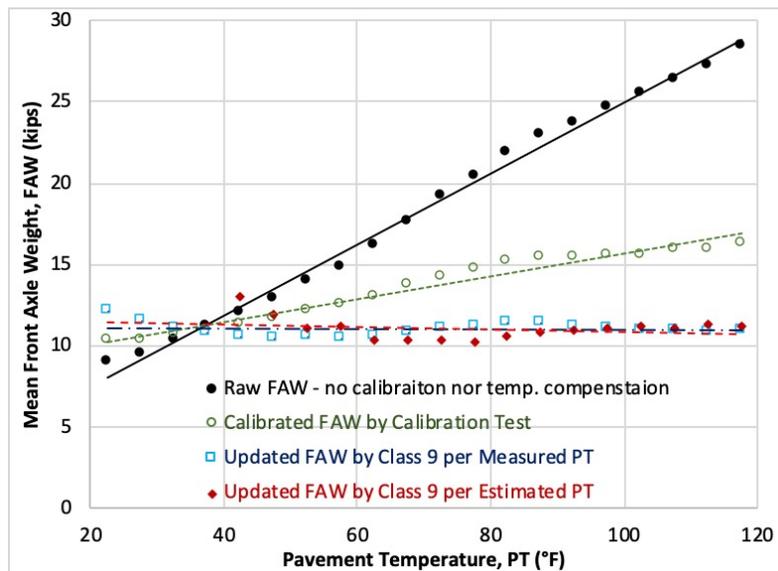
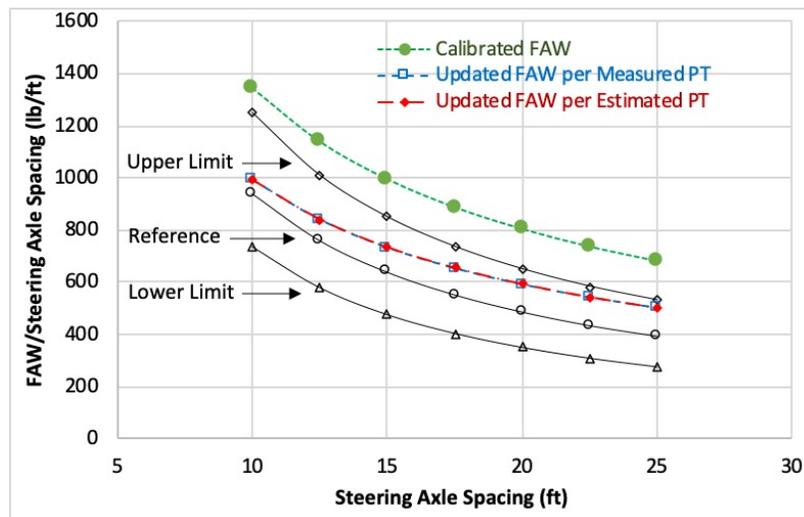


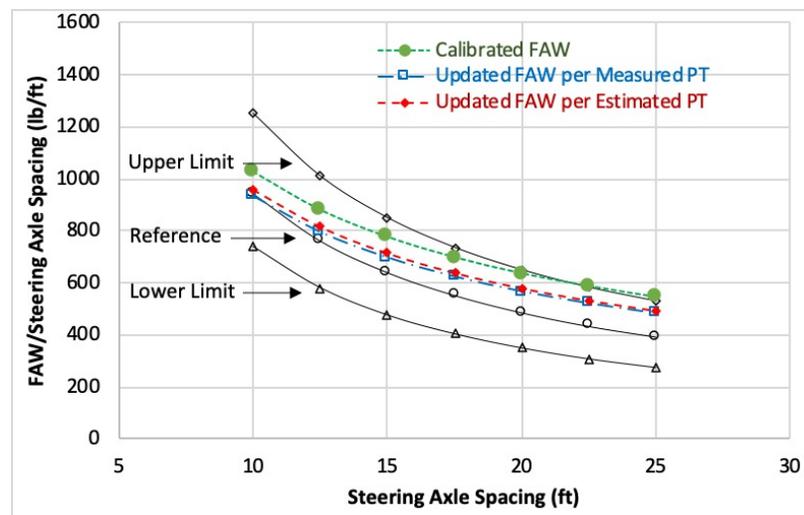
Figure 19: Updated Mean FAW by Class 9 Truck per Pavement Temperature

After the pavement temperature effect was considered, two methodologies were applied to validate the procedure for temperature compensation. One is to check the WIM data quality based on the logarithmic regression of axle spacing and weights proposed by Southgate (2001), and the other is to compare the correlation between FAW and GVW with a tendency plot of the LTPP data (Huang 2004; Chou et al., 2016). Figure 20 shows the WIM quality control procedure results by Southgate (2001). He proposed that FAW plots versus the ratio of FAW to the steering axle spacing should produce a smooth logarithmic decay. Figure 20 describes the following. (1) “Calibration FAW” denotes the WIM data corrected by the calibration testing results but not corrected by the temperature. (2) “Updated FAW per Measured PT (Pavement Temperature)” represents the WIM data adjusted by the pavement

temperature and FAW. (3) “Updated FAW per Estimated PT” implies the WIM data corrected by the FAW and the estimated pavement temperature describe in this report. When the temperature effect is not considered (by calibration), the FAW is biased toward the upper limit (12k legal limit + 50) in all lanes. When the pavement temperature is compensated to correct the FAW, the logarithmic regression curve is closed to the reference line and falls within the upper and lower thresholds. Figure 20 shows that the logarithmic regressions obtained by the measured and predicted temperature are very close. This means that the estimated pavement temperature can effectively adjust WIM data's temperature effect as the measured pavement temperature.



(a)



(b)

Figure 20: WIM Quality Check by Southgate Logarithmic Regression; (a) Summer Season and (b) Winter Season

Figure 21 shows the trend between FAW and GVW of Class 9 Trucks. The black rectangular represents the LTPP trend reported in the literature (Chou et al., 2016). The green triangle shows the WIM data trend using a calibration test at a limited temperature range. The red diamond represents the WIM data adjusted by the measured pavement temperature. The blue circle describes the WIM data corrected by the estimated pavement temperature. The LTPP trend shows that the FAW has a linear relationship with the GVW up to 40 kips, then the FAW remains at approx. 11.7 kips regardless of GVW up to 70 kips and the FAW slightly increases as the GVW increases. When the limited temperature range is considered (Calibration Test), this linear trend extends up to 55 kips, and then the FAW lies far above the LTPP trend by up to 3.5 kips. When the measured pavement temperature corrects the WIM data (red diamond), the linear trend is very close to the LTPP relationship, and the FAW after 40 kips of GVW remains similar to the LTPP trend. When the estimated pavement temperature is used to adjust the WIM data, a similar trend as measured pavement temperature was observed. The results show that the estimated pavement temperature can provide similar improvement and accuracy as the measured pavement temperature.

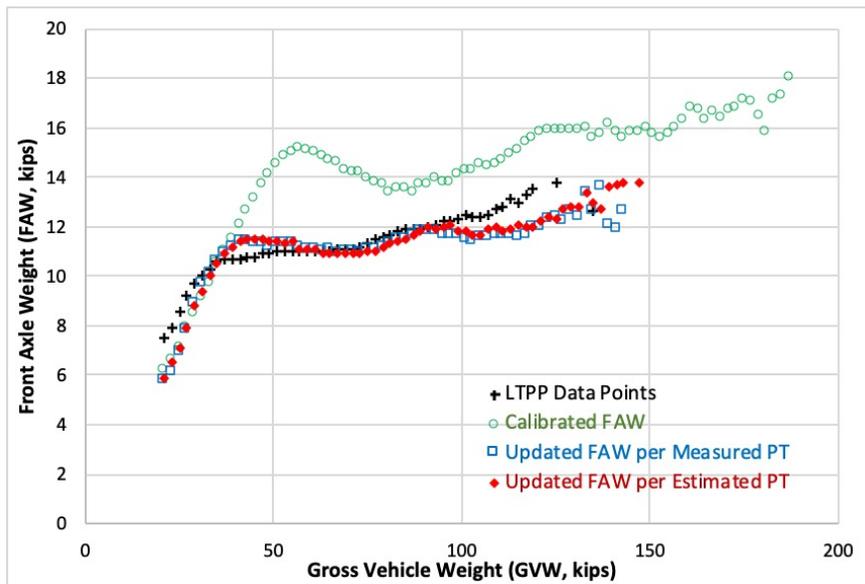
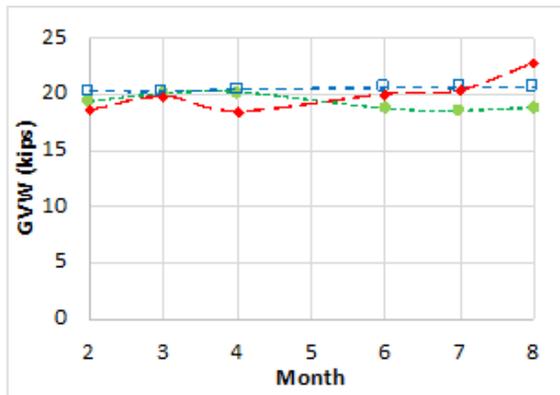


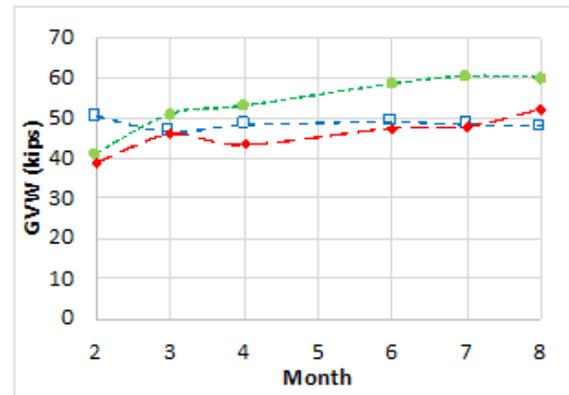
Figure 21: FAW and GVW Relationship Before and After Temperature Compensation

Figure 22 and Figure 23 show the average GVW of each FHWA classification per month. It shows that although the pavement and ambient temperature increases from February to August, the average GVW per each classification is much more consistent after the weight was adjusted to compensate for the

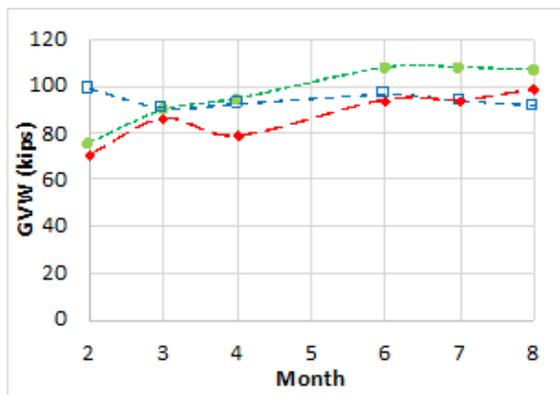
measured pavement temperature effect. The estimated pavement temperature also can effectively change the WIM data, so that the average GVW per classification remains similar regardless of ambient temperature.



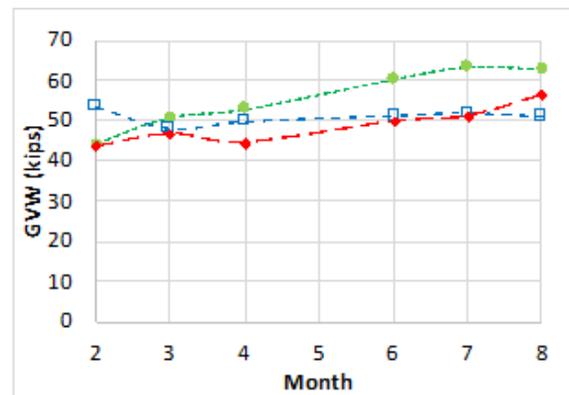
(a) Class 5



(b) Class 6



(c) Class 7

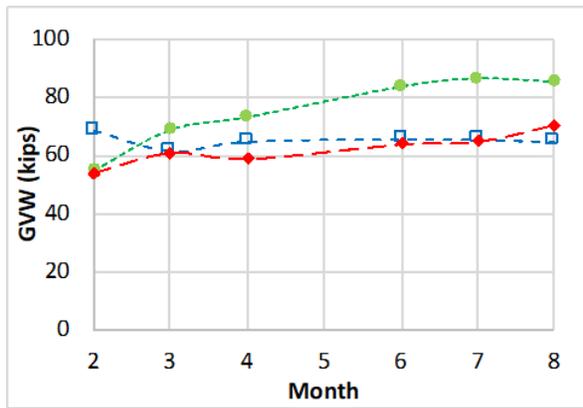


(d) Class 8

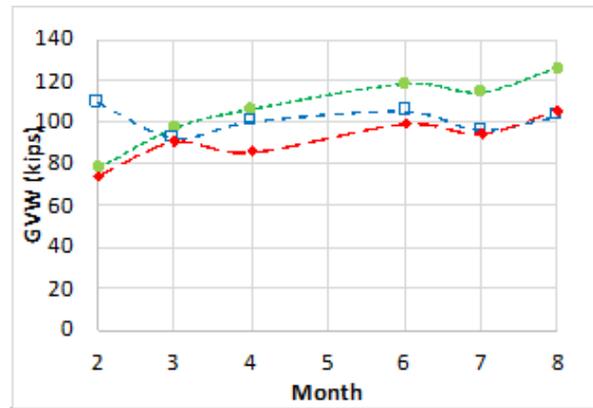
-●-●- Calibrated FAW
 -□-□- Updated FAW per Measured PT
 -◆-◆- Updated FAW per Estimated PT

(e) Legend

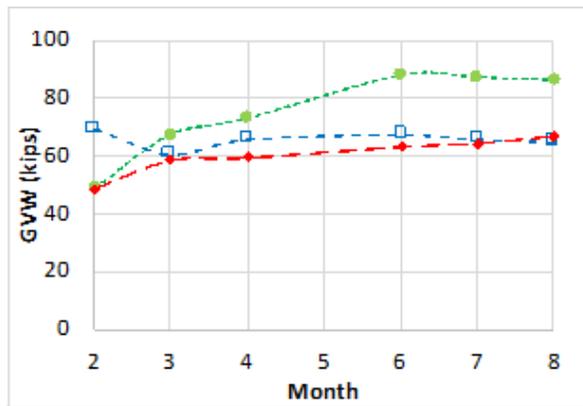
Figure 22: Monthly Average GVW per Classification Adjusted per Measured and Estimated Pavement Temperature 1 (Class 5, Class 6, Class 7, and Class 8)



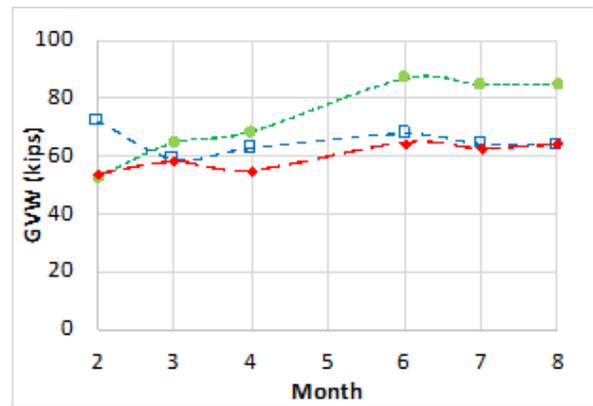
(a) Class 9



(b) Class 10



(c) Class 11



(d) Class 12

- - ● - - Calibrated FAW
 - - □ - - Updated FAW per Measured PT
 - - ◆ - - Updated FAW per Estimated PT

(e) Legend

Figure 23: Monthly Average GVW per Classification Adjusted per Measured and Estimated Pavement Temperature 2 (Class 9, Class 10, Class 11, and Class 12)

Section 6: Conclusion and Recommendations

This project aims to estimating the infrastructure damage costs incurred by the overweight permit trucks, comparing the permit fee policies between states to evaluate the average permit fee, and developing the protocol to update the WIM data to improve its accuracy.

The infrastructure damage cost models for bridges and pavements due to overweight trucks in New Jersey were borrowed from the team's previous research. The damage cost models were then applied to the overweight permit data obtained from the New Jersey Department of Transportation to estimate the OW permit records' damage. The reasons behind using the permit data are that the permit records provide the origin-destination (O-D) and their routes, and the weight (gross and axle) and configuration (spacing). The O-D route provides all the links between mileposts, which includes the bridge numbers and pavement segments. The bridge damage cost associated with OW permit trucks was determined depending on the bridge type (deck and girder) and material (steel and concrete). Similarly, the pavement damage cost associated with OW permit trucks was calculated depending on the roadway type (thick and thin pavement) and corridor types (interstate, state, and local).

The analysis shows that the bridge damage associated with permit trucks is approximate 1/3 (37%) of all infrastructure damages, while the pavement damage due to permit trucks is approximate 2/3 (63%). The collected OW permit fee by single OW permit trucks was approx. 46% of the total infrastructure damages to bridges and pavement. The number of OW permit that pays the OW tonnage fee for a single trip was approx. 55% of all OW permit trucks. In other words, the collected OW permit fee was approx. \$2,105,112 per year, while the total infrastructure damage due to OW permits that pay the OW tonnage fee was approx. \$2,530,635. The average permit fee in New Jersey for the OW truck was approx. \$121 per truck, while the infrastructure damage costs \$145 per truck or 20% higher than the permit fee. Therefore, the OW permit trucks pay 20% less than what they damaged the infrastructure, and the fee structure or tonnage fee would need to update to recoup the damage. However, this is not the case for New York, which issues a flat fee permit wiof40 per single travel. If the same infrastructure damage cost of \$145 per truck is assumed, the difference between infrastructure damage and the collected permit fee would be much higher than NJ.

The PVDF sensor is very susceptible to pavement temperature, and the accuracy will drift tremendously depending on the environmental conditions. Therefore, the calibration of the WIM system is a critical step to improve the accuracy of WIM data. The procedure must also cover a similar range of temperatures to the one-year variation to reach reliable calibration factors. Since the pavement temperature is not always available, this report presented a methodology to estimate the pavement temperature based on the ambient temperature, which is still available from the nearby weather station. It was found that the estimated maximum pavement temperatures provide a better approximation to the identity line than the ones for minimum pavement temperature. When the

pavement temperature is not available, the estimated pavement temperature can effectively compensate for WIM data's temperature effect. The adjusted WIM data using the proposed approach provides similar accuracy as the WIM data corrected by the measured pavement temperature.

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Appendix 1: State Permit Policies

State	Permit Information Link	Fee Schedule	Online Application
AL	https://www.dot.state.al.us/maweb/OverSize&OverweightPermitInformation.html	https://www.dot.state.al.us/maweb/permitFees.html	Yes
AK	http://www.dot.state.ak.us/mscve/index.cfm?go=mscve.permits&CFID=1647322&CFTOKEN=96835346	http://www.dot.state.ak.us/mscve/permits/forms/Permit_Fees.pdf	Yes
AZ	https://www.azdot.gov/motor-vehicles/enforcement/commercial-vehicle-permits/general-permit-information/oversize-overweight-permits	N/A	Yes
AR	https://www.arkansashighways.com/highway_police/oversize_overweight_permits.aspx	https://www.arkansashighways.com/highway_police/2019%20PERMIT%20RULES.pdf	Yes
CA	http://www.dot.ca.gov/trafficops/permits/index.html		No
CO	https://www.codot.gov/business/permits/truckpermits/documents	https://www.codot.gov/business/permits/truckpermits/documents/lcvfyis.pdf	Yes
CT	https://ct.gov/dot/osow	N/A	Yes
DE	https://www.deldot.gov/osow/application/	https://www.deldot.gov/osow/application/faq	Yes
FL	https://www.fdot.gov/maintenance/owodpermits.shtm	https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/maintenance/str/owodp/schedule-of-fees.pdf?sfvrsn=d37c7453_0	Yes
GA	http://www.dot.ga.gov/PS/Permits/OversizePermits	N/A	Yes
HI	https://hidot.hawaii.gov/highways/home/doing-business/guide-to-permits/oversized-and-overweight-vehicles-on-state-highways/	N/A	No
ID	https://trucking.idaho.gov/permits/	https://itd.idaho.gov/wp-content/uploads/2018/02/Permit_Manual.pdf	Yes
IL	http://idot.illinois.gov/doing-business/permits/Oversize-and-Overweight-Permits/index	http://idot.illinois.gov/Assets/uploads/files/Doing-Business/Specialty-Lists/Highways/Permits/table2.pdf	Yes
IN	https://www.in.gov/dor/4243.htm	https://www.in.gov/dor/files/osowhandbook.pdf	No

State	Permit Information Link	Fee Schedule	Online Application
IA	https://iowadot.gov/mvd/motorcarriers/oversize-overweight-trip-permits	TBU	Yes
KS	https://www.ksdot.org/permit_links.asp	https://www.k-trips.com/Kansas%20Permit%20Price%20List.pdf	Yes
KY	https://drive.ky.gov/motor-carriers/Pages/Purchase-Overweight-Over-Dimensional-Permits.aspx	https://transportation.ky.gov/Organizational-Resources/Forms/TC%2095-10.pdf	Yes
LA	http://wwwsp.dotd.la.gov/Business/Pages/Get_a_Permit.aspx	http://wwwsp.dotd.la.gov/Business/LaGeaux_Docs/Rules%20and%20Regulations.pdf	Yes
ME	https://www.maine.gov/sos/bmv/commercial/olpermits.html	N/A	Yes
MD	https://www.roads.maryland.gov/Index.aspx?PageId=58	https://www.roads.maryland.gov/oots/permit_fees.pdf	Yes
MA	https://www.mass.gov/commercial-truck-permits	https://www.mass.gov/files/documents/2017/10/30/700cmr8.pdf	Yes
MI	https://www.michigan.gov/mdot/0,4616,7-151-9623_26662_26679_27267_48606-182174--,00.html	N/A	Yes
MN	http://www.dot.state.mn.us/cvo/oversize/index.html	https://www.dot.state.mn.us/cvo/oversize/pdf/permittypesfees.pdf	Yes
MS	https://www.expresspass.ms.gov/trucking/instruct.htm	N/A	Yes
MO	https://www.modot.org/OSOW	https://www.modot.org/sites/default/files/documents/Fees%5B1%5D.pdf	No
MT	https://www.mdt.mt.gov/business/mcs/permits.shtml	https://www.mdt.mt.gov/other/webdata/external/mcs/mcs_100_fees.pdf	Yes
NE	https://dot.nebraska.gov/business-center/permits/truck/	https://dot.nebraska.gov/media/2786/rules-regs-chapter-3.pdf	Yes
NV	https://www.nevadadot.com/doing-business/commercial-vehicles/commercial-vehicle-permits	https://www.nevadadot.com/doing-business/commercial-vehicles/commercial-vehicle-permits/applications-and-permit-fees	Yes
NH	https://www.nh.gov/dot/org/operations/highwaymaintenance/overhaul/index.htm	https://www.nh.gov/dot/org/operations/highwaymaintenance/overhaul/documents/osowpermitmailinapplication.pdf	Yes

State	Permit Information Link	Fee Schedule	Online Application
NJ	https://www.state.nj.us/transportation/feight/trucking/oversize.shtm	https://nj.gotpermits.com/njpass/Content/state/NJ/PublicMaterials/Fee-Schedule.pdf	Yes
NM	TBU	http://realfile.tax.newmexico.gov/NewMexicoTruckersGuide.pdf	Yes
NY	https://www.dot.ny.gov/nypermits	https://www.dot.ny.gov/nypermits/special-hauling-permits/fees	Yes
NC	https://connect.ncdot.gov/business/trucking/Pages/overpermits.aspx	https://connect.ncdot.gov/business/trucking/Documents/Oversize%20Overweight%20Permit%20Handbook.pdf	Yes
ND	https://www.nd.gov/ndhp/motor-carrier-operations/e-permits	https://www.nd.gov/ndhp/sites/www/files/documents/Permits/9-6%20handout.pdf	Yes
OH	http://www.dot.state.oh.us/Divisions/Operations/Maintenance/Permits/Pages/default.aspx	http://www.dot.state.oh.us/Divisions/Operations/Maintenance/Permits/Anon/Fee%20Schedule%201-02-19.pdf	Yes
OK	http://www.swpermitsok.com/	http://www.swpermitsok.com/NSW%2012-3/Test/PDF/permit%20fees%202015.pdf	Yes
OR	https://www.oregon.gov/ODOT/MCT/Pages/OregonTruckingOnline.aspx	https://www.oregon.gov/ODOT/MCT/Pages/Over-Dimension.aspx	Yes
PA	https://www.penndot.gov/Doing-Business/Permits/HaulingInformation/Pages/default.aspx	https://www.penndot.gov/Doing-Business/Permits/HaulingInformation/Documents/2017%20Permit%20Fees%20version3.pdf	No
RI	TBU	https://www.ri.gov/subscriber/docs/osow/osow_20170911.pdf	Yes
SC	https://www.scdot.org/business/permits-osow.aspx	N/A	Yes
SD	http://sdtruckinfo.com/permitting.aspx	N/A	Yes
TN	https://www.tn.gov/tdot/central-services/oversize---overweight-permits.html	https://www.tn.gov/content/dam/tn/tdot/central-services/Ch%201680-07-01%20--%20Overweight%20over-dimensional%20movements%20-%20Final%20Rules%202017.pdf	Yes
TX	https://www.txdmv.gov/motor-carriers/oversize-overweight-permits/texas-size-weight-limits	https://www.txdmv.gov/publications-carriers/doc_download/3415-	Yes

State	Permit Information Link	Fee Schedule	Online Application
		table-of-permit-fees-and-credit-card-payments	
UT	https://www.udot.utah.gov/main/f?p=100:pg:0:::V,T:383	https://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:5203,	Yes
VT	https://dmv.vermont.gov/commercial-services/permits	https://dmv.vermont.gov/commercial-services/fees	No
VA	https://www.dmv.virginia.gov/commercial/#mcs/programs/overload/index.asp	https://www.dmv.virginia.gov/general/#hauling.asp	No
WA	http://www.wsdot.wa.gov/CommercialVehicle/permitting.htm	http://www.wsdot.wa.gov/publications/manuals/fulltext/M3037/PDG.pdf	Yes
WV	https://transportation.wv.gov/highways/maintenance/hauling_permits/Pages/default.aspx	https://transportation.wv.gov/highways/maintenance/hauling_permits/Pages/Permit-Types.aspx	Yes
WI	https://wisconsindot.gov/Pages/dmv/com-drv-vehs/mtr-car-trkr/osowgeneral.aspx	https://wisconsindot.gov/Documents/formdocs/mv2600.pdf	Yes
WY	http://www.dot.state.wy.us/home/trucking_commercial_vehicles/commercial_permits.html	N/A	Yes
DC	https://ddot.dc.gov/page/permits-and-tags-oversized-and-overweight-vehicle-operation	https://ddot.dc.gov/node/482382	Yes