NEW MEXICO DEPARTMENT OF TRANSPORTATION

RESEARCH BUREAU

Innovation in Transportation

DEVELOPMENT OF TECHNICAL GUIDANCE FOR THE ASSESSMENT OF OVERSIZE AND OVERWEIGHT VEHICLE PERMIT FEES IN NEW MEXICO (PHASE 2)

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16. Abstract
The adverse impact of oversize/overweight (OS/OW) vehicles on pavements and bridges is a concern in New Mexico and other states due to the infrastructure damage caused by the large loads that are transported on the highway system. Moneys generated from permit fees should cover administrative and technical costs associated with the permitting process. In addition, the generated funds should cover a justifiable portion of the costs associated with maintenance, repair, and reconstruction of pavements and bridges impacted by OS/OW vehicles. In general, for single-trip permits, the fees are charged based primarily on how much the gross vehicle weight (GVW) of the permit load exceeds the legal load limits. This project was conducted for the New Mexico Department of Transportation (NMDOT) to evaluate the current OS/OW single-trip permit fees charged in New Mexico and provide options for adjusting the fees to correlate with the (1) fees charged in neighboring states and (2) projected damage imposed to pavements and bridges. The project was conducted by way of three tasks. In Task 1, the most common OS/OW load configurations in the state of New Mexico (based on GVW, size, distance traveled, and axle configurations) and most common OS/OW travel routes are determined. The primary deliverable from this task is the selection of ten OS/OW vehicle configurations (including two fracking coil vehicles). In Task 2, the costs of mobilizing the vehicles identified in Task 1 (based on similar route types and travel distances in Arizona, Colorado, Oklahoma and Texas) are evaluated in comparison to New Mexico. A simple revenue assessment is also provided based on various adjustments to the current permit fees that would bring New Mexico on par with neighboring states. In Task 3, literature reviews of current and developing methods used by state Departments of Transportation (DOTs) to quantify damage caused by OS/OW vehicle traffic to pavements and bridges are conducted. Attention is given to collecting the information necessary to conduct technical analyses of damage, identifying information gaps that could limit the analyses, and developing a multi-stage framework for quantifying the effects of damage and associated costs. The basic framework is based primarily on pavement damage as characterized by equivalent single axle loads (ESALs) and secondarily on bridge damage as defined by changes in the condition ratings in OS/OW traffic corridors.

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Final Report

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PREFACE

The purpose of this study is to provide technical guidance on the assessment of the oversize/overweight (OS/OW) fee structure in New Mexico. The project objectives are 1) to determine whether the current New Mexico fee structure is comparable to neighboring states for the most common OS/OW load configurations, including the most common combinations of gross vehicle weight/size, distance traveled, and axle configurations; 2) to determine the impact of overweight trucks on New Mexico transportation infrastructure; and 3) formulate a draft fee structure for New Mexico that would generate revenues comparable to neighboring states.

NOTICE

DISCLAIMER

Abstract:
The adverse impact of oversize/overweight (OS/OW) vehicles on pavements and bridges is a concern in New Mexico and other states due to the infrastructure damage caused by the large loads that are transported on the highway system. Moneys generated from permit fees should cover administrative and technical costs associated with the permitting process. In addition, the generated funds should cover a justifiable portion of the costs associated with maintenance, repair, and reconstruction of pavements and bridges impacted by OS/OW vehicles. In general, for single-trip permits, the fees are charged based primarily on how much the gross vehicle weight (GVW) of the permit load exceeds the legal load limits. This project was conducted for the New Mexico Department of Transportation (NMDOT) to evaluate the current OS/OW single-trip permit fees charged in New Mexico and provide options for adjusting the fees to correlate with the (1) fees charged in neighboring states and (2) projected damage imposed to pavements and bridges. The project was conducted by way of three tasks. In Task 1, the most common OS/OW load configurations in the state of New Mexico (based on GVW, size, distance traveled, and axle configurations) and most common OS/OW travel routes are determined. The primary deliverable from this task is the selection of ten OS/OW vehicle configurations (including two fracking coil vehicles). In Task 2, the costs of mobilizing the vehicles identified in Task 1 (based on similar route types and travel distances in Arizona, Colorado, Oklahoma and Texas) are evaluated in comparison to New Mexico. A simple revenue assessment is also provided based on various adjustments to the current permit fees that would bring New Mexico on par with neighboring states. In Task 3, literature reviews of current and developing methods used by state Departments of Transportation (DOTs) to quantify damage caused by OS/OW vehicle traffic to pavements and bridges are conducted. Attention is given to collecting the information necessary to conduct technical analyses of damage, identifying information gaps that could limit the analyses, and developing a multi-stage framework for quantifying the effects of damage and associated costs. The basic framework is based primarily on pavement damage as characterized by equivalent single axle loads (ESALs) and secondarily on bridge damage as defined by changes in the condition ratings in OS/OW traffic corridors.

Table of Contents

List of Figures

List of Tables

1. TASK 1

TYPICAL LOAD CONFIGURATIONS IN NEW MEXICO

The primary deliverable from Task 1 is the selection of 10 representative OS/OW scenarios. Identifying these load configurations and routes is necessary for consistency purposes to directly compare the total fees charged by New Mexico and neighboring states (Task 2) and to quantify the damage to pavements and bridges (Task 3). In this research, a data-driven approach is used that includes collecting data, analyzing patterns employing statistical and probabilistic methods, and utilizing the data to provide insights about permit loads that could benefit the NMDOT in different ways. A data-driven approach provides the means to make more confident decisions and be more proactive and effective in allocating resources.

1.1. Permit data

The data analyzed in Task 1 were provided by ProMiles Software Development Corporation over the time period of March 2015 to August 2018. Four important data files were provided which are described below in accordance with the file extensions:

***.dbf:** database file that includes detailed information about the permitted vehicles.
***.prj:** data file used by multiple programs to save project data and settings; such files may also include reference to other files or projects.
***.shx:** shape index file associated with the AutoCAD computer aided drafting software program.
***.shp:** shapefile in digital vector storage format that stores geometric location and associated attribute information.

The vehicle specifications were imported from the database (dbf) files. Table 1 shows the 18 items provided in the specifications.

Table 1. Vehicle specification list provided in database files.

Year	Month	Permit ID
Permit Type	Vehicle Length	Vehicle Width
Vehicle Height	Gross Vehicle Weight (GVW)	Start Date
End Date	Load Description	Vehicle Type
Fees	Company	Traveled Distance
Axle Weight	Axle Width	Axle Spacing

The shape (shp) files contain data about the routes traveled and together with the database (dbf) files provided the information needed by the research team to identify the routes for each vehicle. All data files previously described were processed via the Python 3.8 programming language. The most up-to-date primary and secondary roads for New Mexico and the county subdivisions were acquired from publicly available shapefile data provided by the U. S. Census Bureau, Department of Commerce [6, 7].

1.2. Statistical framework

In this section, the general statistical framework for determining the most common vehicles for the various permit categories is described. The process starts by obtaining the truck distribution in each permit category based on the number of axles. Then, the truck populations are divided based on the number of axles and the associated GVW distributions. These populations are then reduced to include just the vehicles falling within one standard deviation of the mean GVW and the corresponding distributions of axle spacings and weights are processed. The mean values of each distribution are then used to define the load configuration of the most common truck for the permit category. Subsequently, the distribution of traveled distances are determined and a specific vehicle is picked from the real permits as the representative scenario for the permit category under consideration and the traveled routes are evaluated to complete the scenario. Figure 1 summarizes the statistical framework for the scenario selections.

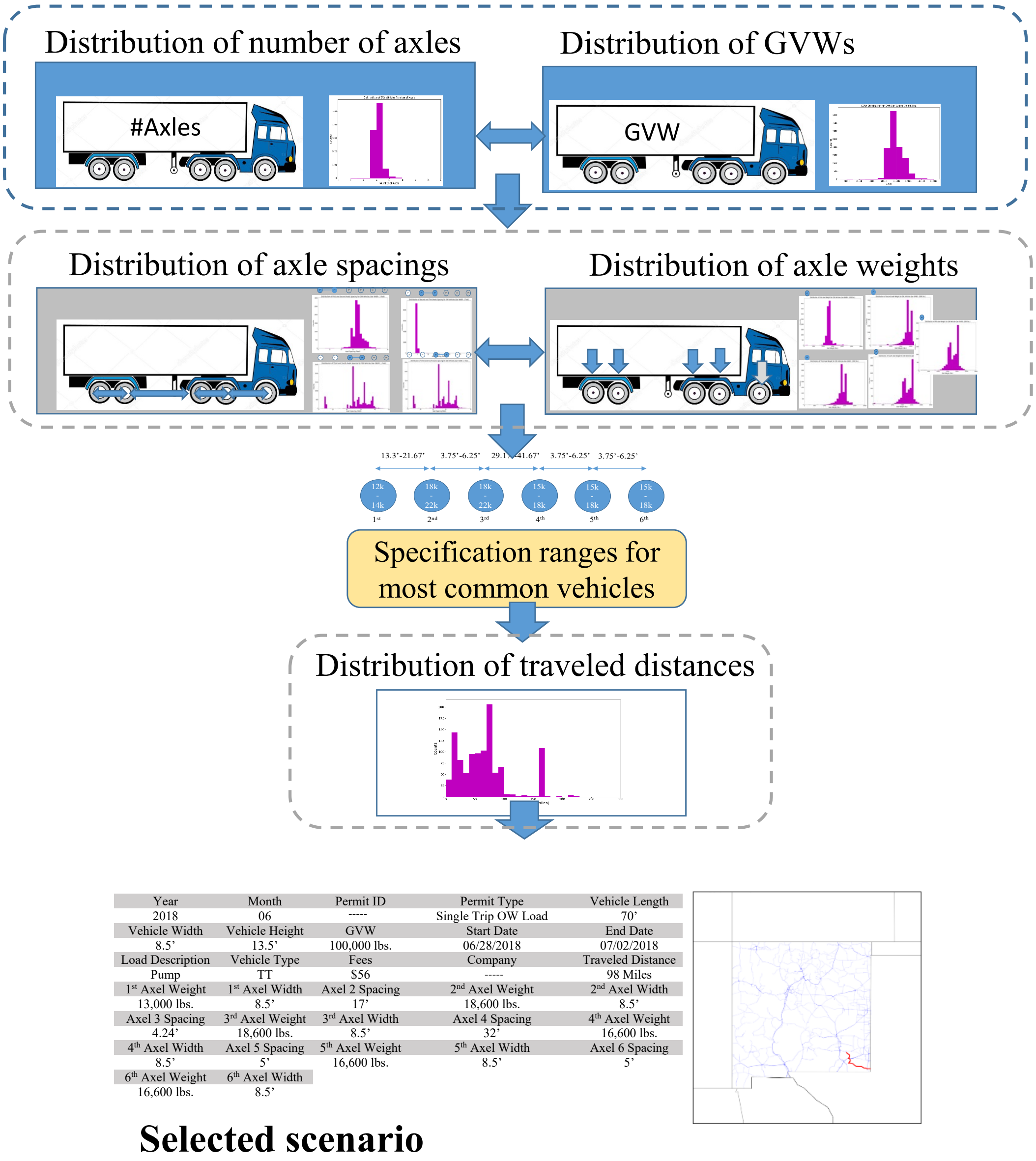

Figure 1. Flowchart of framework for selecting scenarios from permit type categories.

1.3. Permit categories

Two major factors were considered to identify the most important permit categories in this study: high load effects on transportation infrastructure (i.e., load and frequency) and high revenue potential for maintenance and preservation. Table 2 summarizes the various types and associated number of issued permits in New Mexico between March 2015 and August 2018.

Figure 2 presents the normalized data in a pie chart. Five permit categories were considered the most important based on the load magnitudes and frequencies, and the potential damage to bridges and pavements in New Mexico. From the five categories, the following scenarios were selected for investigation in consultation with the NMDOT Technical Panel and approved:

- one scenario from Single Trip Overweight (OW) Load permits,
- two scenarios from Single Trip Super Load permits,
- one scenario from Single Trip Oversized (OS) Load permits,
- one scenario from Single Trip OS/OW Load permits, and
- two scenarios from Single Trip Self-Propelled permits.

In the next sections, the seven scenarios are presented in more detail.

Table 2. Permit types and number of issued permits in each category.

Permit Type	Number of Permits
Caravan and Fuel Permit	675
Government Single Trip OS/OW Load	195
Single Trip Excessive Weight Oilfield Pr	34
Single Trip Manufactured Home	23,754
Single Trip OS Hay Load	76
Single Trip OS[1] Load	103,515
Single Trip OS/OW[2] Load	68,851
Single Trip OS/OW Wrecker	34
Single Trip OW Liquid Load	2
Single Trip OW[3] Load	10,173
Single Trip Self-Propelled[4]	5,258
Single Trip Super Load[5]	6,126
Temporary Fuel Permit	3,852
Trip Permit	154,076
Trip and Fuel Permit	85,159

[1]Oversize (OS): truck exceeding permitted size limits
[2]Oversize/overweight (OS/OW): truck exceeding permitted size and weight limits
[3]Overweight (OW): truck exceeding permitted weight limits
[4]Self-propelled: truck propelled by own motor or fuel
[5]Super load: truck with GVW > 250,000 lbs

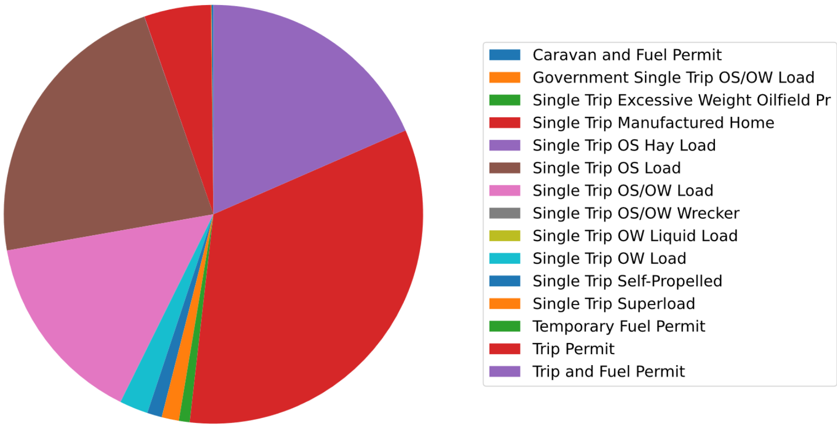

Figure 2. Pie chart of issued permits.

Scenario #1 (Single Trip OW Load)

The Single Trip OW Load category accounts for 10,173 permits (see Table 2). Approximately 59% of the permits in this category (5,994 permits) have GVWs between 90,000 lbs. and 110,000 lbs. (Figure 3) with 5 and 6 axles (Figure 4). Histograms of the axle loads and axle spacings for all of the vehicles permitted under this category were analyzed to extract the most common case (see Appendix A). Figure 5 shows the distribution of traveled distances for these vehicles. According to the data, 900 vehicles traveled between 10 and 100 miles. Table 3 shows the final vehicle specifications that were selected to represent the Single Trip OW Load category and the route of the representative vehicle is shown in Figure 6.

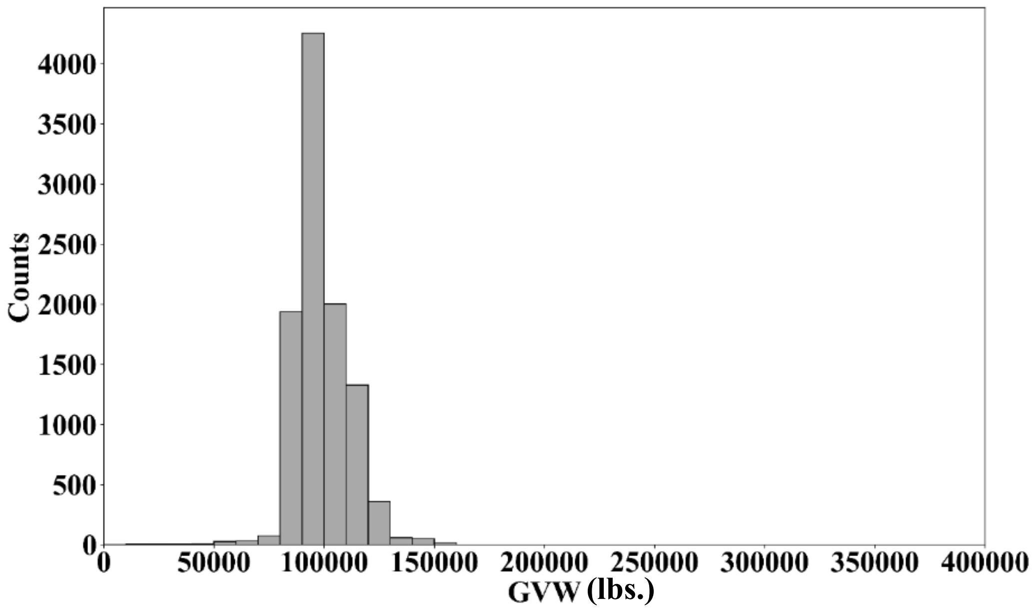

Figure 3. GVWs for all vehicles in Single Trip OW Load category.

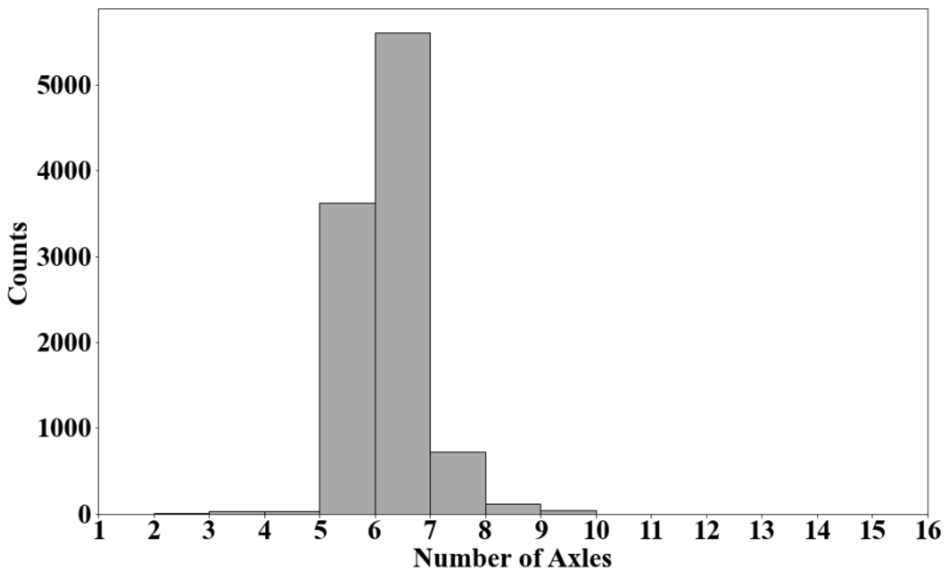

Figure 4. Number of axles for all vehicles in Single Trip OW Load category.

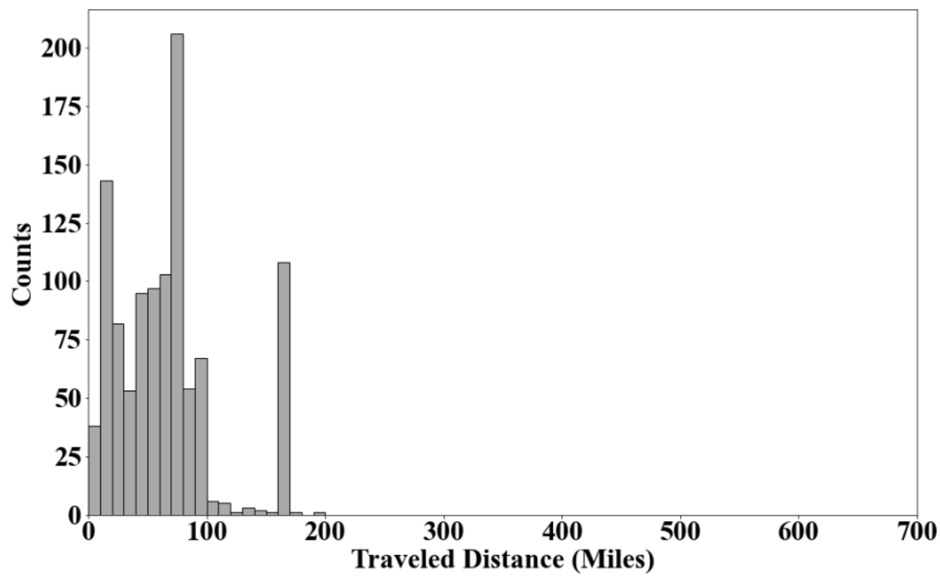

Figure 5. Traveled distances for select 5-to-6 axle vehicles in Single Trip OW Load category.

Table 3. Scenario #1 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2018	06	-----	Single Trip OW Load	70’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
8.5’	13.5’	100,000 lbs.	06/28/2018	07/02/2018
Load Description	Vehicle Type	Fees	Company	Traveled Distance
Pump	TT	$56	-----	98 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
13,000 lbs.	8.5’	17’	18,600 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
4.24’	18,600 lbs.	8.5’	32’	16,600 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	Axle 6 Spacing
8.5’	5’	16,600 lbs.	8.5’	5’
6th Axle Weight	6th Axle Width			
16,600 lbs.	8.5’			

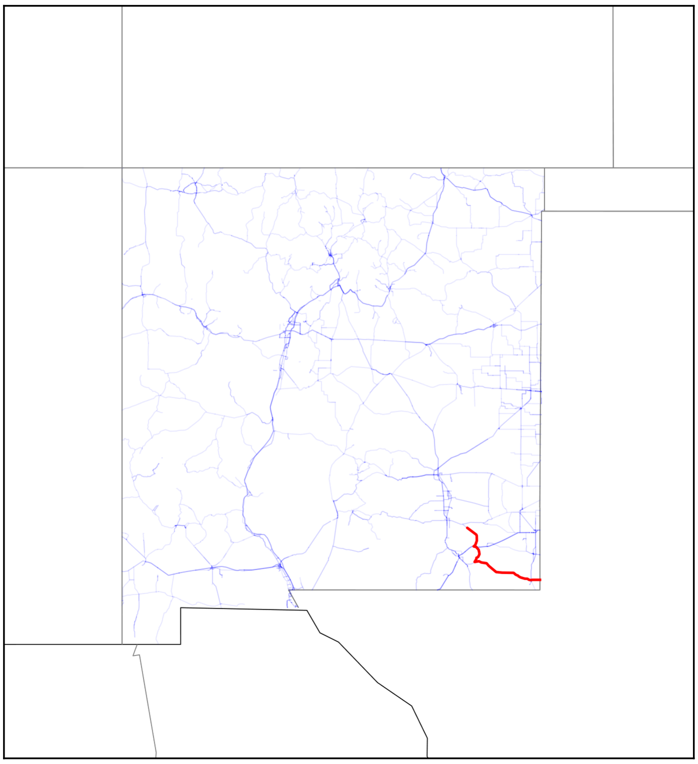

Figure 6. Scenario #1 permit load route.

Scenarios #2 and #3 (Single Trip Super Load)

Among all permit categories, the vehicles in the Single Trip Super Load category have the maximum GVWs. Consequently, two scenarios from this permit category were identified. The distribution of the number of axles for this category is shown in Figure 7. The two vehicle groups with 9 and 13 axles were dominant and were used to determine the two scenarios.

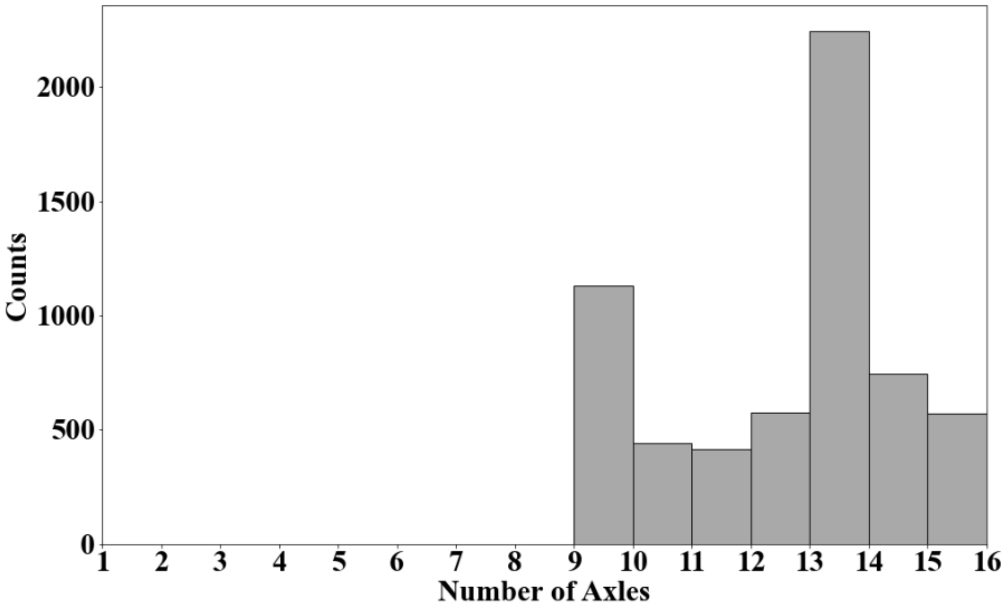

Figure 7. Number of axles for Single Trip Super Load category.

Scenario #2 (13 Axles)

The distribution of GVW for vehicles in the Single Trip Super Load permit category with 13 axles is shown in Figure 8. To narrow down the cases, vehicles with GVWs between 230,000 lbs. and 260,000 lbs. were selected.

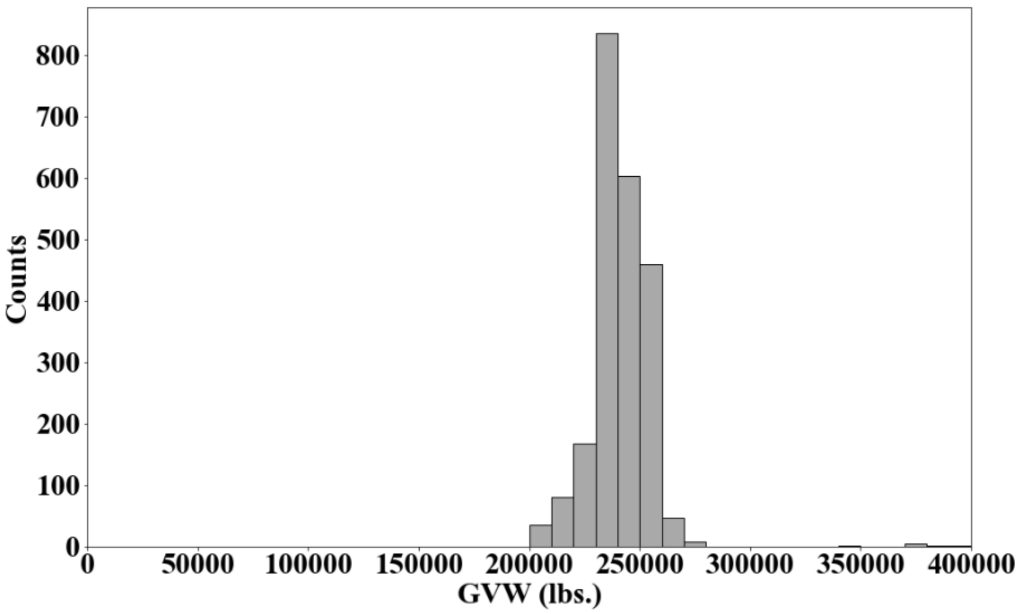

Figure 8. GVWs for 13-axle vehicles in Single Trip Super Load category.

Based on the distributions of axle weights and spacings (see Appendix A), the ranges of axle spacings and weights are determined for vehicles in this permit category. Figure 9 displays the distribution of traveled distances for vehicles within the determined ranges in this category.

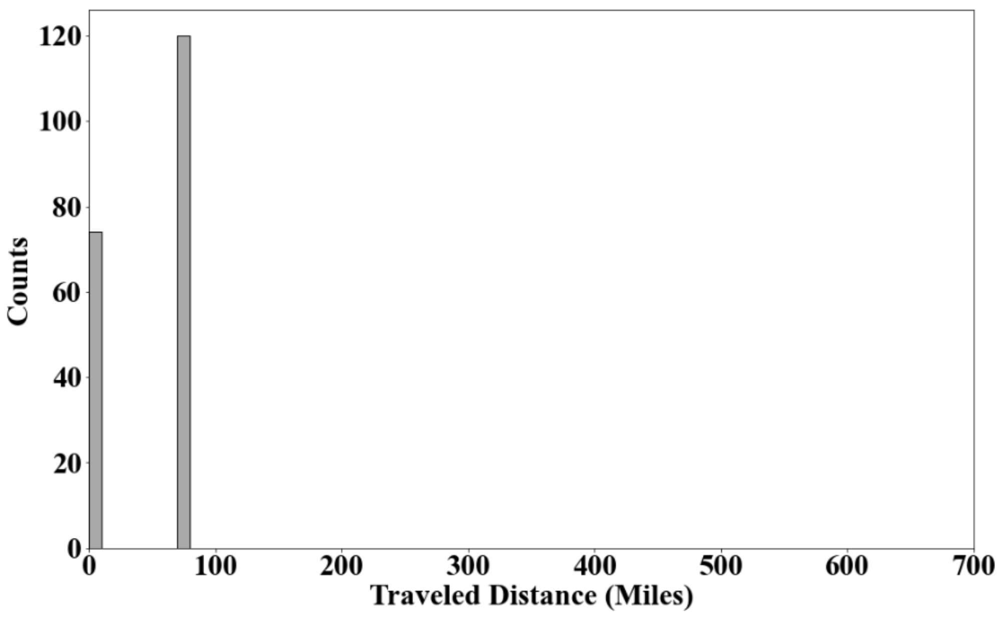

Figure 9. Traveled distances for select 13-axle vehicles in the Single Trip Super Load category.

All the filtered vehicles traveled less than 10 miles or between 70 to 80 miles. The selected scenario representing the vehicles within the Single Trip Super Load category is shown in Table 4 and the associated route is displayed in Figure 10. The vehicle traveled 76 miles in New Mexico and used routes US-60, US-70, NM-114, and State Highway 206.

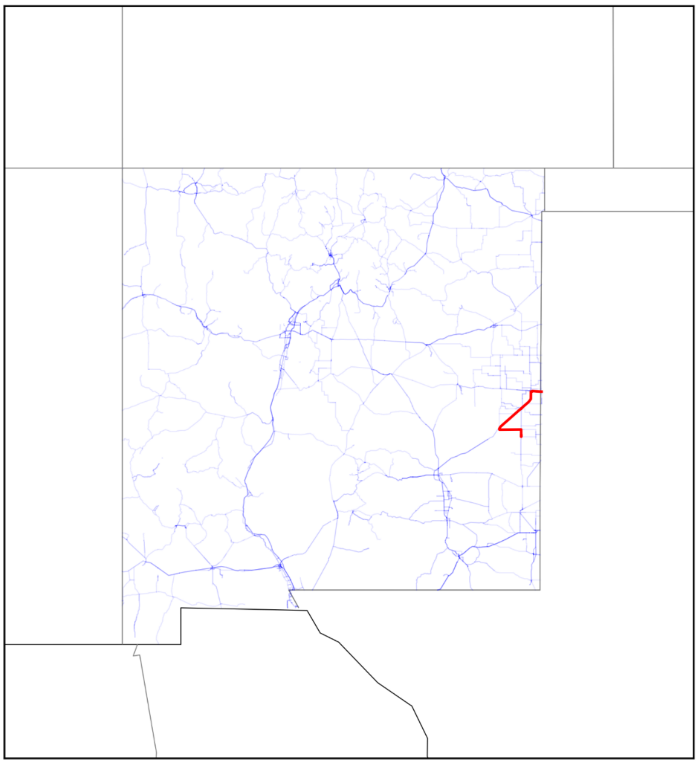

Figure 10. Scenario #2 permit load route.

Table 4. Scenario #2 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2015	11	-----	Single Trip Super Load	185’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
12.5’	15.41’	246,000 lbs.	11/03/2015	11/05/2015
Load Description	Vehicle Type	Fees	Company	Traveled Distance
WIND TOWER MID	TT	$176	-----	76 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
18,000 lbs.	8.5’	14.4’	19,000 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
4.5’	19,000 lbs.	8.5’	4.5’	19,000 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	Axle 6 Spacing
8.5’	16.3’	19,000 lbs.	10’	5’
6th Axle Weight	6th Axle Width	Axle 7 Spacing	7th Axle Weight	7th Axle Width
19,000 lbs.	10’	5’	19,000 lbs.	10’
Axle 8 Spacing	8th Axle Weight	8th Axle Width	Axle 9 Spacing	9th Axle Weight
85.3’	19,000 lbs.	10’	5’	19,000 lbs.
9th Axle Width	Axle 10 Spacing	10th Axle Weight	10th Axle Width	Axle 11 Spacing
10’	5’	19,000 lbs.	10’	16’
11th Axle Weight	11th Axle Width	Axle 12 Spacing	12th Axle Weight	12th Axle Width
19,000 lbs.	10’	5’	19,000 lbs.	10’
Axle 13 Spacing	13th Axle Weight	13th Axle Width		
5’	19,000 lbs.	10’		

Scenario #3 (9 Axles)

The distribution of GVW for vehicles in the Single Trip Super Load category with 9 axles is shown in Figure 11. The distributions of axle spacings and axle weights of the vehicles within the Single Trip Super Load category with nine axles are presented in Appendix A. Figure 12 shows the associated distribution of traveled distances. The majority of the trucks traveled between 150 to 200 miles. The selected scenario #3 is outlined in Table 5 and the specific truck route is shown in Figure 13. The vehicle traveled 192 miles on routes NM-53, I-40, and I-25.

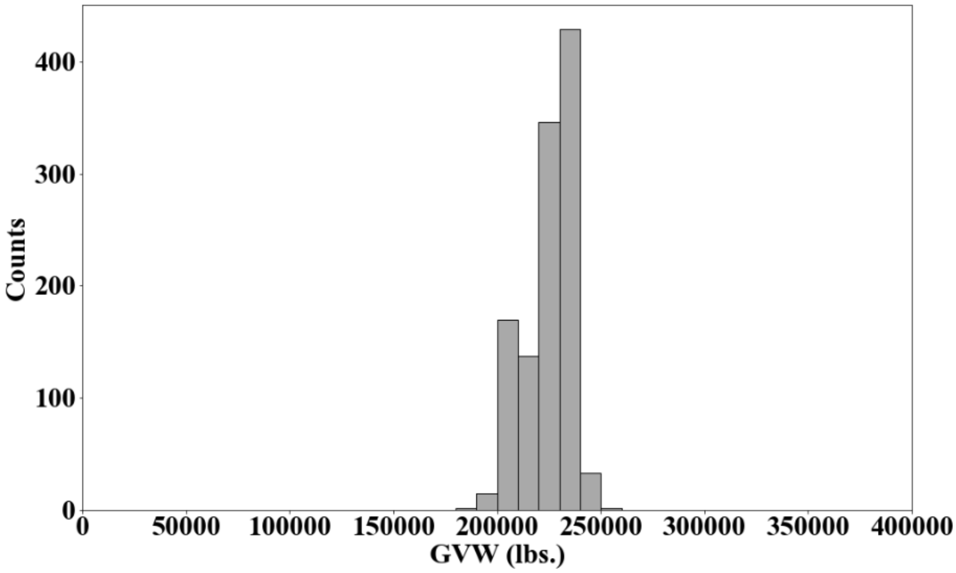

Figure 11. GVWs for 9-axle vehicles in Single Trip Super Load category.

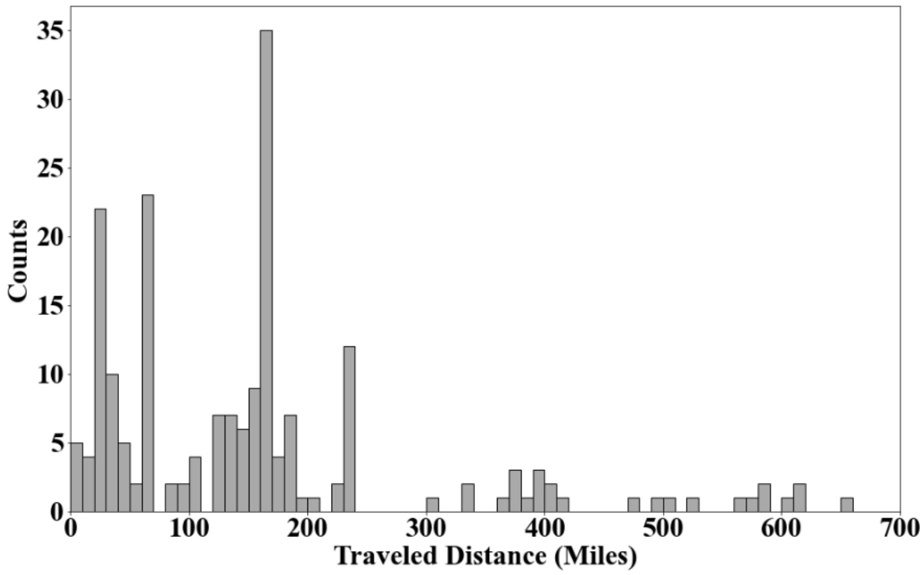

Figure 12. Traveled distances for select 9-axle vehicles in Single Trip Super Load category.

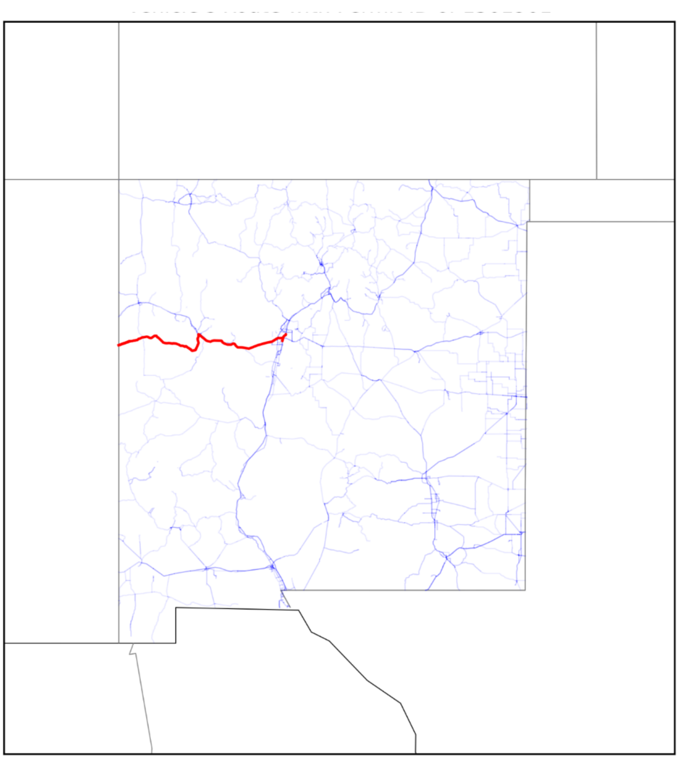

Figure 13. Scenario #3 permit load route.

Table 5. Scenario #3 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2016	10	-----	Single Trip Super Load	110’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
14’	15’	226,000 lbs.	10/19/2016	10/23/2016
Load Description	Vehicle Type	Fees	Company	Traveled Distance
CAT 390 EXCAVATOR	TT	$325	-----	192 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
20,000 lbs.	8’	14.5’	22,000 lbs.	8’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
5’	22,000 lbs.	8’	14.5’	28,750 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	Axle 6 Spacing
10’	5.75’	28,750 lbs.	10’	39.83’
6th Axle Weight	6th Axle Width	Axle 7 Spacing	7th Axle Weight	7th Axle Width
26,250 lbs.	10’	5.75’	26,250 lbs.	10’
Axle 8 Spacing	8th Axle Weight	8th Axle Width	Axle 9 Spacing	9th Axle Weight
12.58’	26,250 lbs.	10’	5.75’	26,250 lbs.
9th Axle Width				
10’				

Scenario #4 (Single Trip OS/OW Load)

The Single Trip OS/OW Load category includes 68,851 cases. Because of its large frequency and considerable GVW, the effect of this permit vehicle category on the state's infrastructure can be significant. Figure 14 shows the distribution of number of axles for vehicles in the Single Trip OS/OW category. As shown, vehicles with 5 and 6 axles are the most common vehicles in this category. The distribution of GVW for vehicles in the Single Trip OS/OW Load category with 5 axles is shown in Figure 15 and Figure 16 shows the associated traveled distances. The second largest group of vehicles traveled between 350 to 420 miles. Among all trucks in this range, the one with the specifications given in Table 6 was selected to represent the Single Trip OS/OW category since the associated route spanned across New Mexico as shown in Figure 17. The vehicle traveled 396 miles on I-40 and NM-53.

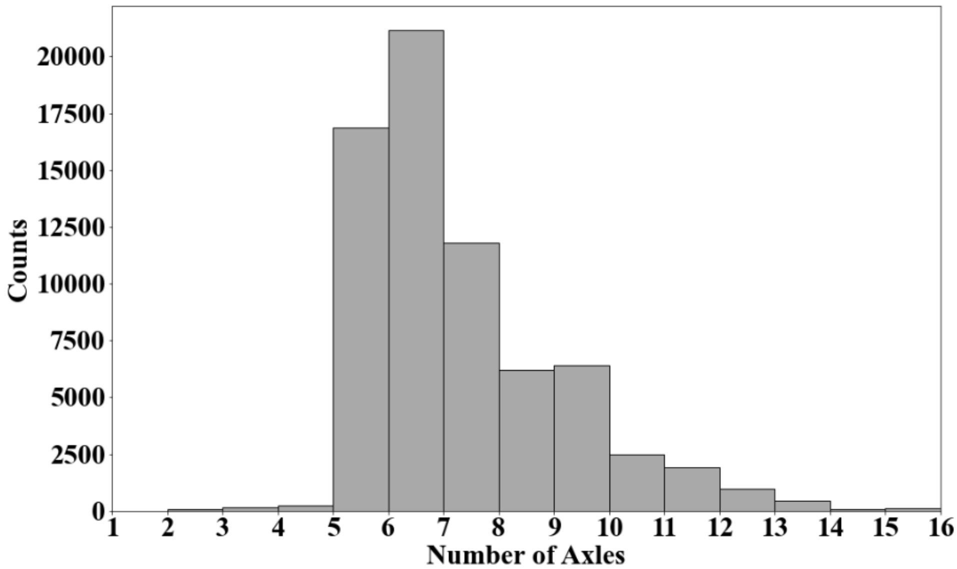

Figure 14. Number of axles for all vehicles in Single Trip OS/OW Load category.

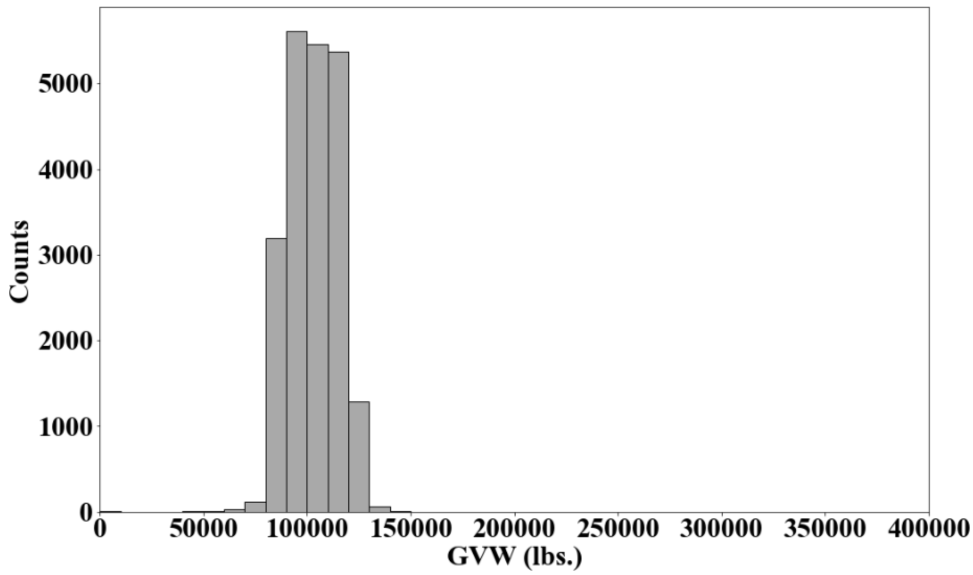

Figure 15. GVWs for 5-axle vehicles in Single Trip OS/OW Load category.

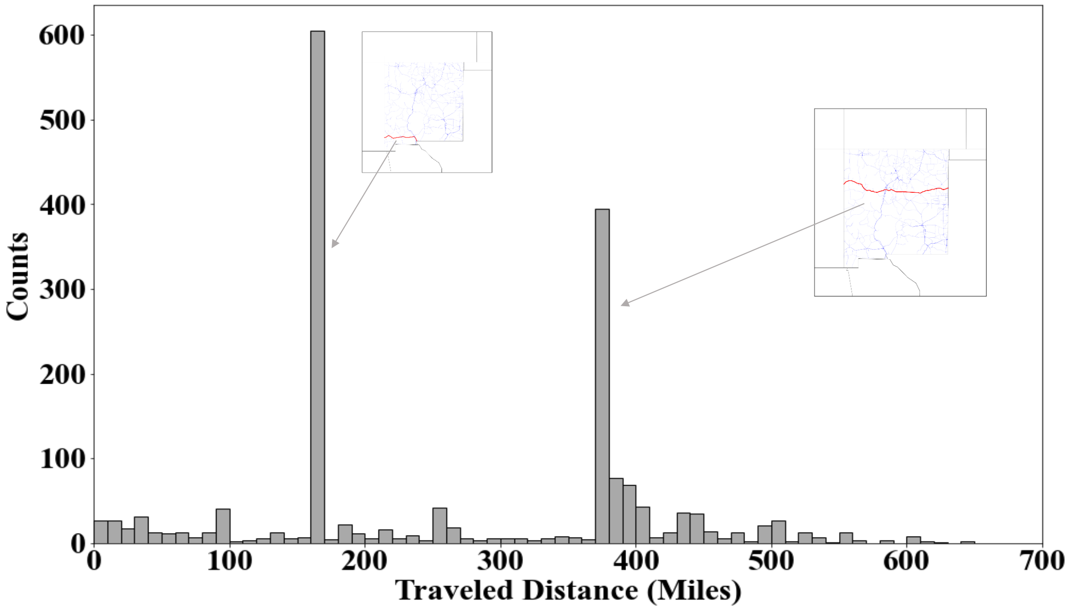

Figure 16. Traveled distances for select 5-axle vehicles in Single Trip OS/OW Load category.

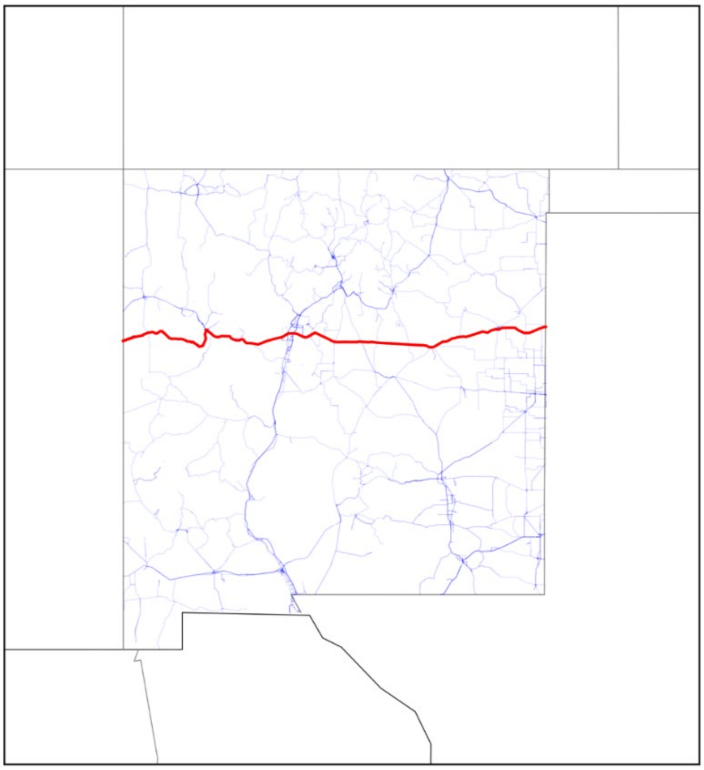

Figure 17. Scenario #4 permit load route.

Table 6. Scenario #4 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2015	10	-----	Single Trip OS/OW Load	75’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
8.5’	14’	90,000 lbs.	10/01/2015	10/03/2015
Load Description	Vehicle Type	Fees	Company	Traveled Distance
DRILL	TT	$41	-----	396 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
12,000 lbs.	8.5’	19.58’	20,000 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
4.1’	20,000 lbs.	8.5’	38’	19,000 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	
8.5’	4.58’	19,000 lbs.	8.5’	

Scenario #5 (Single Trip OS Load)

The Single Trip OS category had 103,515 permits and is the most frequent permit requested of all categories. As a result, the impact of these OS vehicles on the transportation network and the state’s revenue can be significant. One scenario from this permit category was selected. Figure 18 shows the distribution of number of axles in the Single Trip OS category. Five-axle trucks dominate this category. The GVW distribution for 5-axle vehicles in the Single Trip OS category is shown in Figure 19, and Figure 20 shows the associated distribution of traveled distances. The majority of vehicles traveled between 150 to 200 and 350 to 400 miles. The details of the selected scenario are outlined in Table 7 and the corresponding route is displayed in Figure 21. The vehicle traveled 371 miles on interstate I-40.

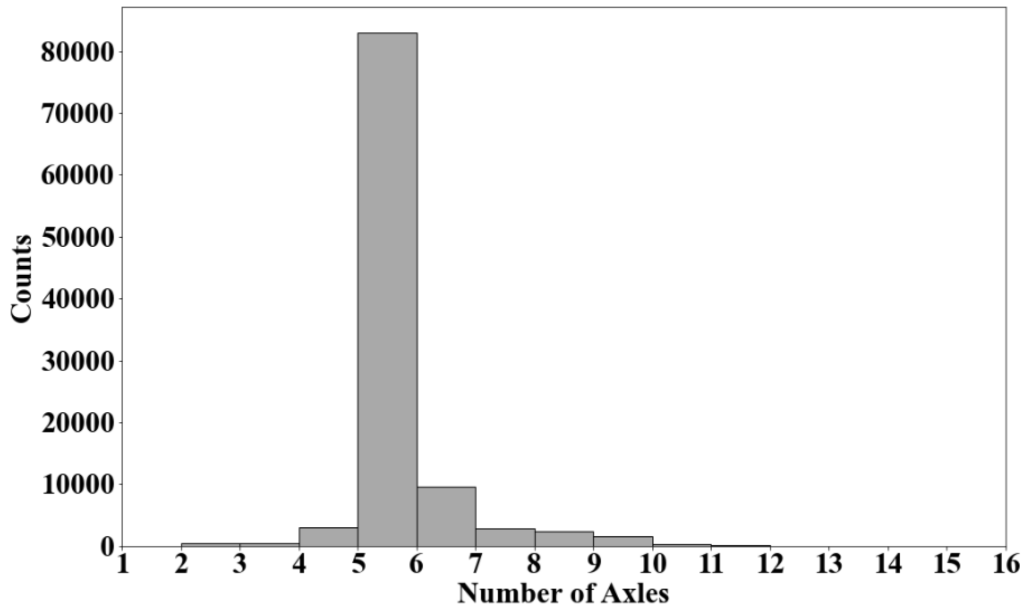

Figure 18. Number of axles for all vehicles in Single Trip OS Load category.

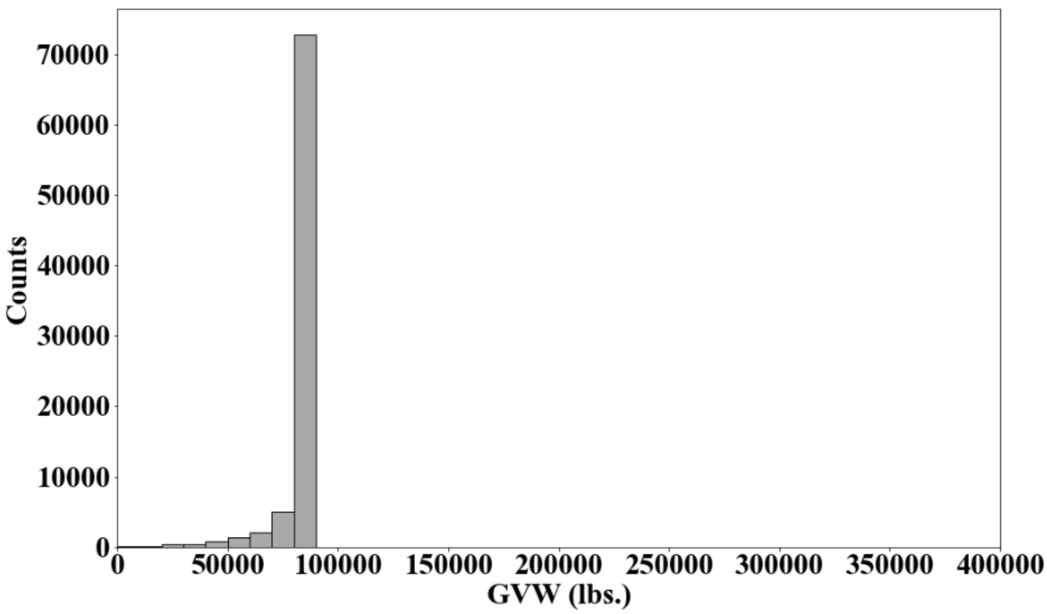

Figure 19. GVWs for 5-axle vehicles in Single Trip OS Load category.

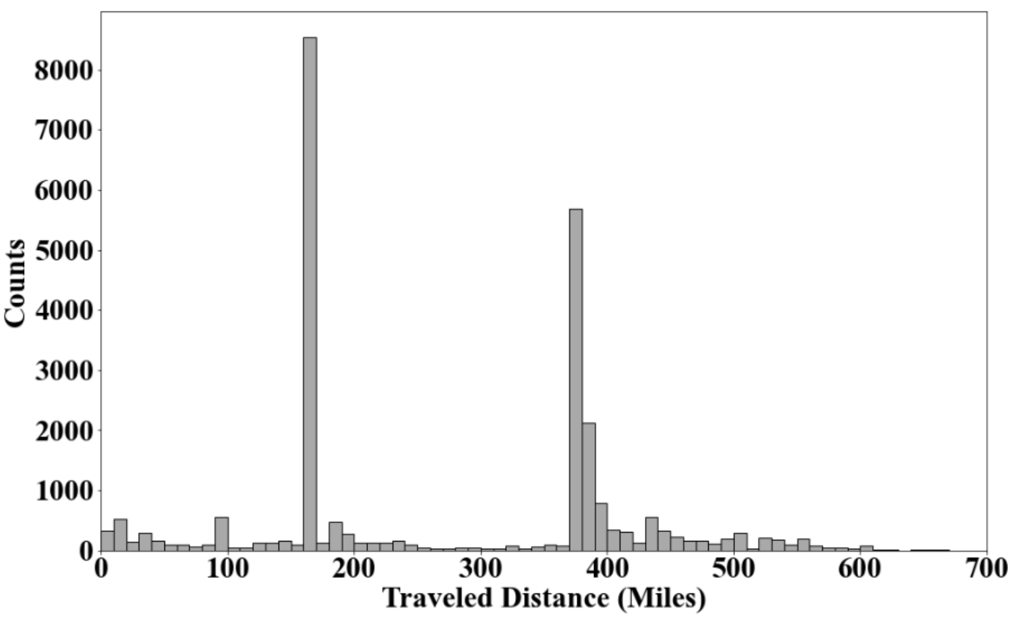

Figure 20. Traveled distances for select 5-axle vehicles in Single Trip OS Load category.

Table 7. Scenario #5 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2018	08	-----	Single Trip OS Load	75’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
9.91’	13.5’	80,000 lbs.	08/10/2018	08/14/2018
Load Description	Vehicle Type	Fees	Company	Traveled Distance
CAT DW6	TT	$25	-----	371 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
12,000 lbs.	8.5’	17.5’	17,000 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
4.5’	17,000 lbs.	8.5’	36’	17,000 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	
8.5’	4.5’	17,000 lbs.	8.5’	

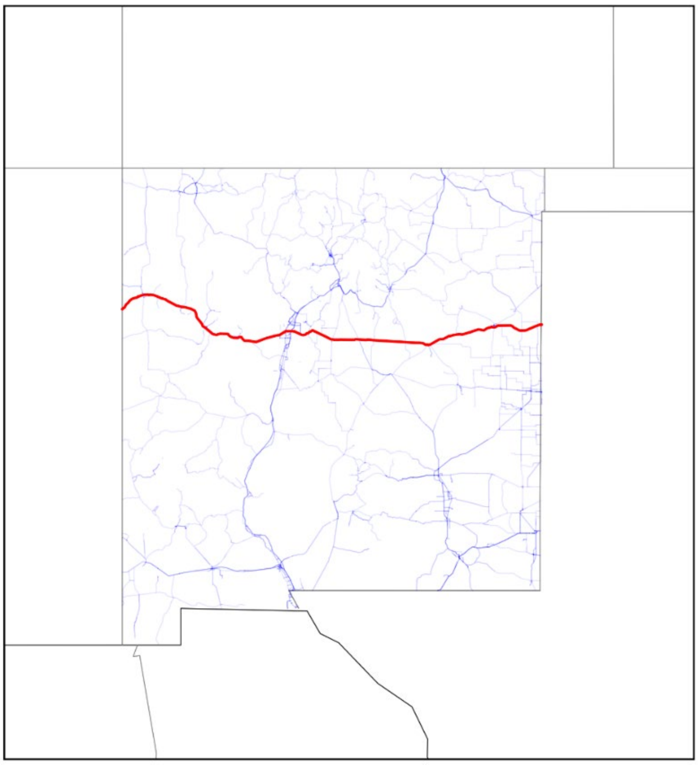

Figure 21. Scenario #5 permit load route.

Scenarios #6 and #7 (Single Trip Self-Propelled Load)

Because of the importance of the Single Trip Self-Propelled category to the oil industry and its potential impact on the NM transportation infrastructures, two scenarios were identified from this category. Figure 22 shows the distribution of the number of axles for all vehicles in this category. Vehicles with 4 and 5 axles are the most common cases; thus, one scenario was selected with 4 axles and one scenario with 5 axles.

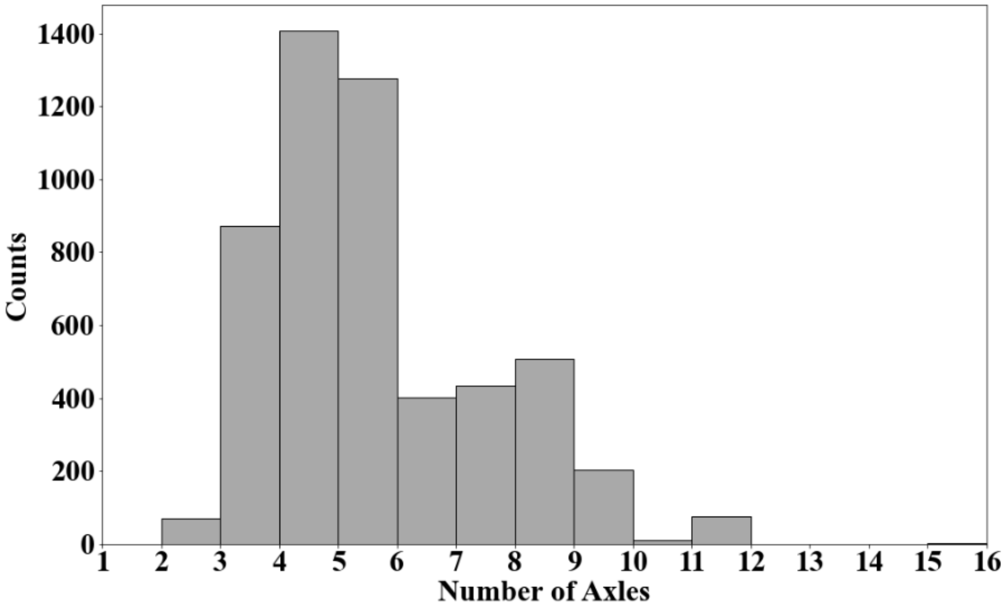

Figure 22. Number of axles for all vehicles in Single Trip Self-Propelled Load category.

Scenario #6 (4 Axles)
Figure 23 shows the GVW distribution for vehicles in the Single Trip Self-Propelled category with 4 axles. Figure 24 shows a large group of vehicles traveled between 10 to 180 miles. The characteristics of the vehicle selected for the Single Trip Self-Propelled category are outlined in Table 8 and the route traveled is displayed in Figure 25. The selected vehicle traveled 78 miles on NM-18, NM-128, NM-31, and Highway 285.

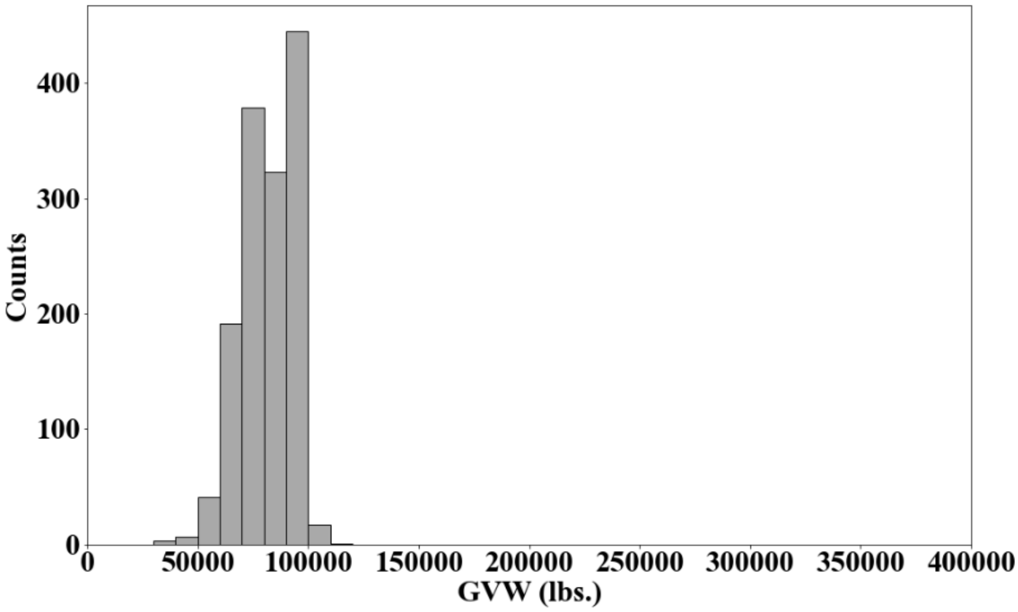

Figure 23. GVWs for 4-axle vehicles in Single Trip Self-Propelled Load category.

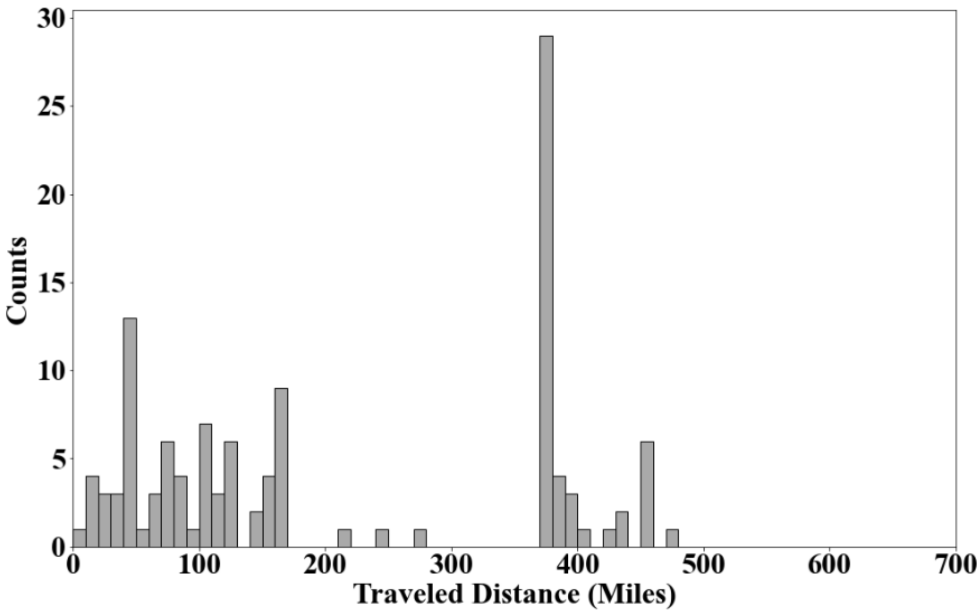

Figure 24. Traveled distances for select 4-axle vehicles in Single Trip Self-Propelled Load category.

Table 8. Scenario #6 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2018	03	-----	Single Trip Self-Propelled	42’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
8.5’	14’	72,000 lbs.	03/14/2018	03/18/2018
Load Description	Vehicle Type	Fees	Company	Traveled Distance
Self-Propelled	CR	$25	-----	78 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
18,000 lbs.	8.5’	17.8’	18,000 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
4.5’	18,000 lbs.	8.5’	4.5’	18,000 lbs.
4th Axle Width				
8.5’				

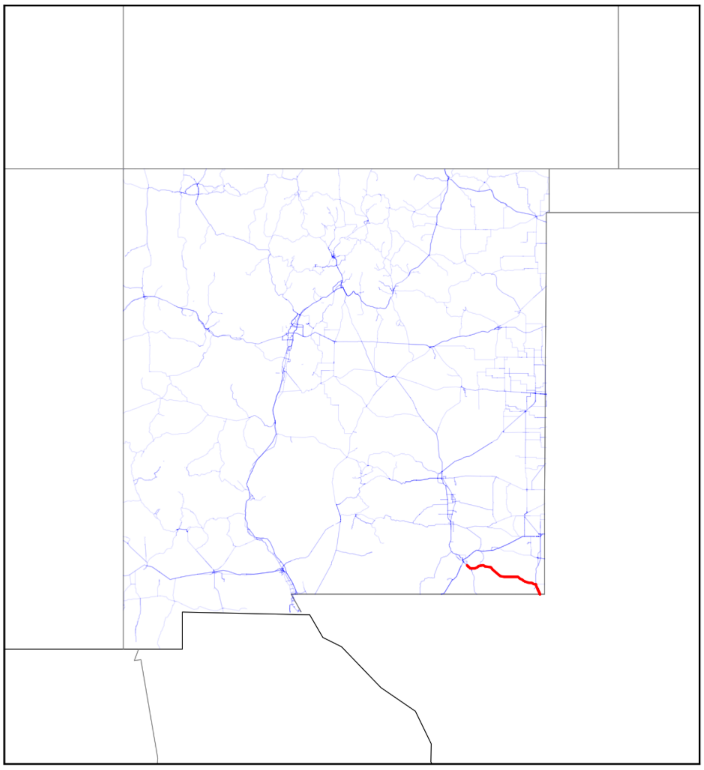

Figure 25. Scenario #6 permit load route.

<u>Scenario #7 (5 Axles)</u>

Figure 26 shows the distribution of GVW for vehicles in the Single Trip Self-Propelled category with 5 axles. Figure 27 shows the majority of the vehicles traveled between 10 to 150 miles. The seventh scenario in the Single Trip Self-Propelled category is outlined in Table 9 and the corresponding route is displayed in Figure 28. The vehicle traveled 78 miles on NM-234 and NM-176.

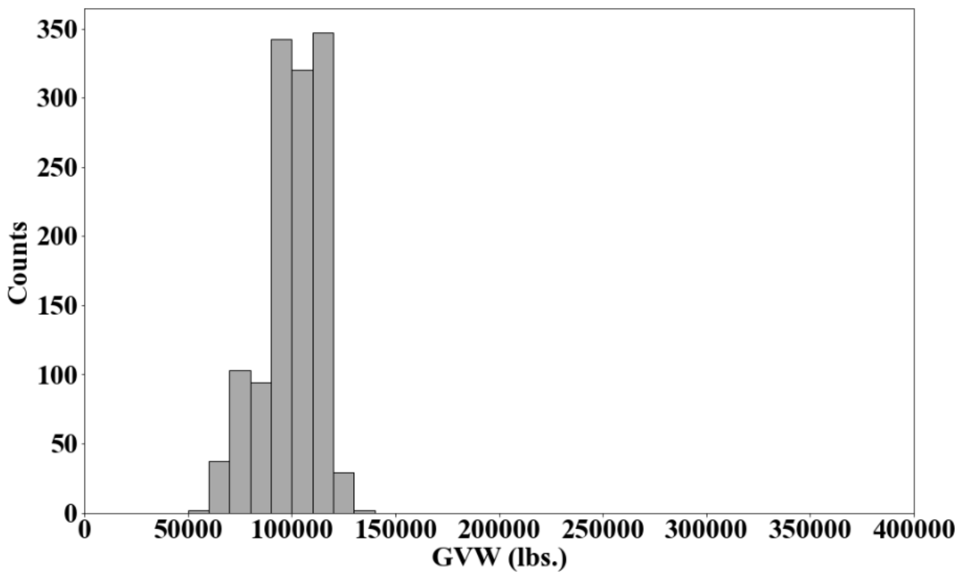

Figure 26. GVWs for 5-axle vehicles in Single Trip Self-Propelled Load category.

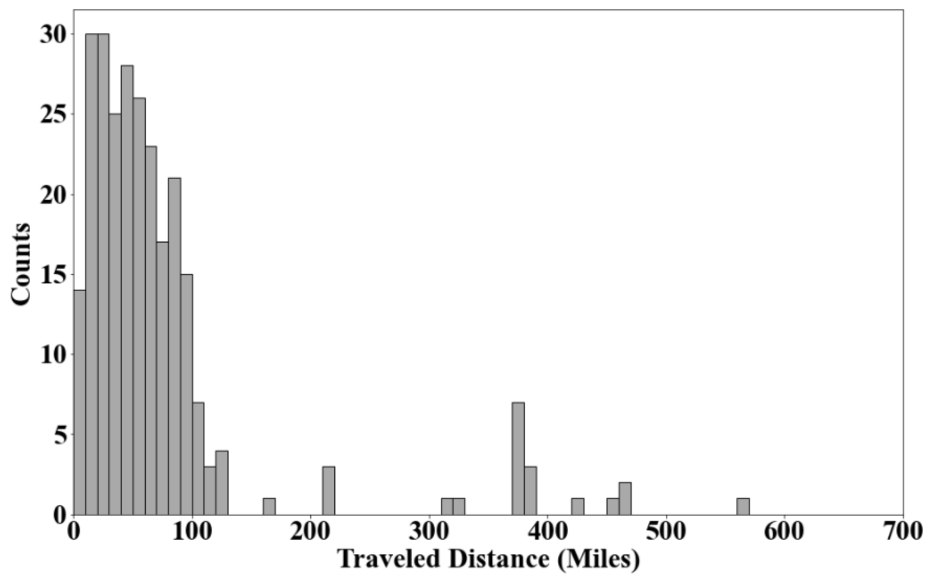

Figure 27. Traveled distances for select 5-axle vehicles in Single Trip Self-Propelled category.

Table 9. Scenario #7 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2017	03	-----	Single Trip Self-Propelled	65.8’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
9.8’	14.41’	110,000 lbs.	03/21/2017	03/25/2017
Load Description	Vehicle Type	Fees	Company	Traveled Distance
Self-Propelled	OR	$37	-----	42 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
20,500 lbs.	8.5’	5’	20,500 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
15’	23,000 lbs.	8.5’	4’	23,000 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	
8.5’	4’	23,000 lbs.	8.5’	

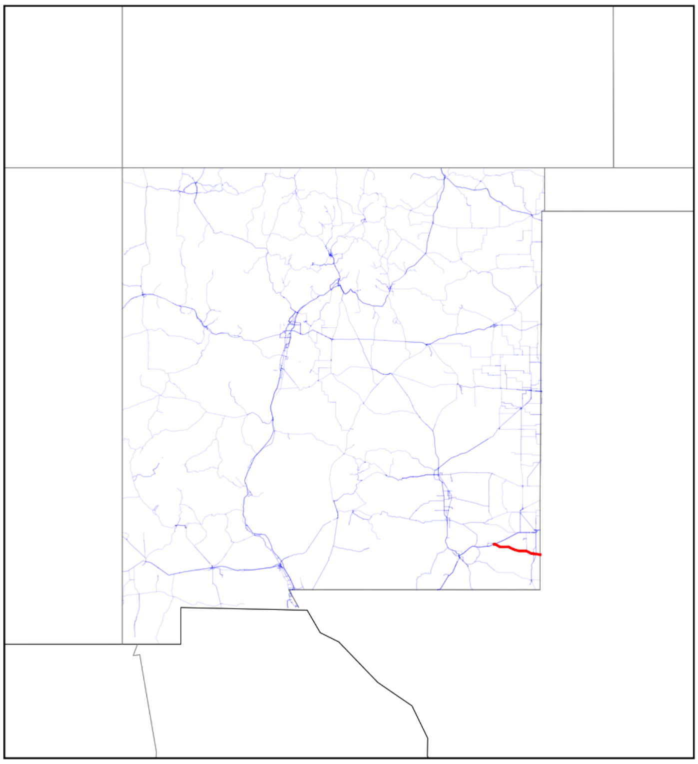

Figure 28. Scenario #7 permit load route.

Scenarios #8 through #10

The final three scenarios, #8 through #10, were provided by the NMDOT Bridge Bureau and consist of coil tubing units with GVWs of 324.1 kips, 255.0 kips, and 303.95 kips. Tables 10 through 15 provide the permit load specifications for these three units. The same traveled route was used for each unit and also provided by the NMDOT Bridge Bureau. The route represents a high overweight vehicle traffic corridor in South-Eastern New Mexico starting at Jal, NM on NM-128 to Carlsbad, NM, and ending at the NM-TX border through Malaga, NM as shown in Figure 29.

Table 10. Scenario #8 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2019	N/A	-----	Single Trip Super Load	122’ 7”
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
14’ 6”	15’ 10”	324,100 lbs.	N/A	N/A
Load Description	Vehicle Type	Fees	Company	Traveled Distance
Coil Tube	Coil Tubing Unit	N/A	-----	123 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
17,000 lbs.	8.5’	6’ 1”	17,000 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
14’ 1”	18,000 lbs.	8.5’	4.5’	18,000 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	Axle 6 Spacing
8.5’	4’ 7”	18,000 lbs.	8.5’	4’ 7”
6th Axle Weight	6th Axle Width	Axle 7 Spacing	7th Axle Weight	7th Axle Width
18,000 lbs.	8.5’	15’ 10”	23,700 lbs.	12’
Axle 8 Spacing	8th Axle Weight	8th Axle Width	Axle 9 Spacing	9th Axle Weight
5’	23,700 lbs.	12’	5’	23,700 lbs.
9th Axle Width	Axle 10 Spacing	10th Axle Weight	10th Axle Width	Axle 11 Spacing
12’	24’ 10”	24,500 lbs.	14.5’	4’ 6”
11th Axle Weight	11th Axle Width	Axle 12 Spacing	12th Axle Weight	12th Axle Width
24,500 lbs.	14.5’	4’ 6”	24,500 lbs.	14.5’
Axle 13 Spacing	13th Axle Weight	13th Axle Width	Axle 14 Spacing	14th Axle Weight
14’ 1”	24,500 lbs.	14.5’	4.5’	24,500 lbs.
14th Axle Width	Axle 15 Spacing	15th Axle Weight	15th Axle Width	
14.5’	4.5’	24,500 lbs.	14’ 6”	

Table 11. Scenario #9 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2018	N/A	-----	Single Trip Super Load	116’ 4”
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
13’ 11”	16’ 8”	255,000 lbs.	N/A	N/A
Load Description	Vehicle Type	Fees	Company	Traveled Distance
Coiled Tubing Unit	Truck Tractor	N/A	-----	123 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
20,000 lbs.	8.5’	15’ 4”	15,000 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
4’ 5”	15,000 lbs.	8.5’	4’ 7”	15,000 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	Axle 6 Spacing
8.5’	4’ 7”	15,000 lbs.	8.5’	10’ 10”
6th Axle Weight	6th Axle Width	Axle 7 Spacing	7th Axle Weight	7th Axle Width
16,000 lbs.	8.5’	4’ 6”	16,000 lbs.	8.5’
Axle 8 Spacing	8th Axle Weight	8th Axle Width	Axle 9 Spacing	9th Axle Weight
4’ 6”	16,000 lbs.	8.5’	22’ 10”	16,200 lbs.
9th Axle Width	Axle 10 Spacing	10th Axle Weight	10th Axle Width	Axle 11 Spacing
10’	4’ 7”	16,200 lbs.	10’	4’ 7”
11th Axle Weight	11th Axle Width	Axle 12 Spacing	12th Axle Weight	12th Axle Width
16,200 lbs.	10’	4’ 7”	16,200 lbs.	10’
Axle 13 Spacing	13th Axle Weight	13th Axle Width	Axle 14 Spacing	14th Axle Weight
4’ 7”	16,200 lbs.	10’	14’ 8”	23,000 lbs.
14th Axle Width	Axle 15 Spacing	15th Axle Weight	15th Axle Width	
8.5’	4’ 8”	23,000 lbs.	8.5’	

Table 12. Scenario #10 permit load specifications.

Year	Month	Permit ID	Permit Type	Vehicle Length
2019	N/A	-----	Single Trip Super Load	118’
Vehicle Width	Vehicle Height	GVW	Start Date	End Date
14’ 6”	15’ 5”	303,950 lbs.	N/A	N/A
Load Description	Vehicle Type	Fees	Company	Traveled Distance
Coil Tubing Reel Trailer #1	Coil Tubing Unit	N/A	-----	123 Miles
1st Axle Weight	1st Axle Width	Axle 2 Spacing	2nd Axle Weight	2nd Axle Width
21,450 lbs.	8.5’	15’	20,625 lbs.	8.5’
Axle 3 Spacing	3rd Axle Weight	3rd Axle Width	Axle 4 Spacing	4th Axle Weight
5’	20,625 lbs.	8.5’	5’	20,625 lbs.
4th Axle Width	Axle 5 Spacing	5th Axle Weight	5th Axle Width	Axle 6 Spacing
8.5’	5’	20,625 lbs.	8.5’	15’
6th Axle Weight	6th Axle Width	Axle 7 Spacing	7th Axle Weight	7th Axle Width
22,000 lbs.	8.5’	5’	22,000 lbs.	8.5’
Axle 8 Spacing	8th Axle Weight	8th Axle Width	Axle 9 Spacing	9th Axle Weight
5’	22,000 lbs.	8.5’	24’ 10”	21,000 lbs.
9th Axle Width	Axle 10 Spacing	10th Axle Weight	10th Axle Width	Axle 11 Spacing
10’ 3”	5’	21,000 lbs.	10’ 3”	5’
11th Axle Weight	11th Axle Width	Axle 12 Spacing	12th Axle Weight	12th Axle Width
23,000 lbs.	10’ 3”	15’	23,000 lbs.	10’ 3”
Axle 13 Spacing	13th Axle Weight	13th Axle Width	Axle 14 Spacing	14th Axle Weight
5’	23,000 lbs.	10’ 3”	5’	23,000 lbs.
14th Axle Width				
10’ 3”				

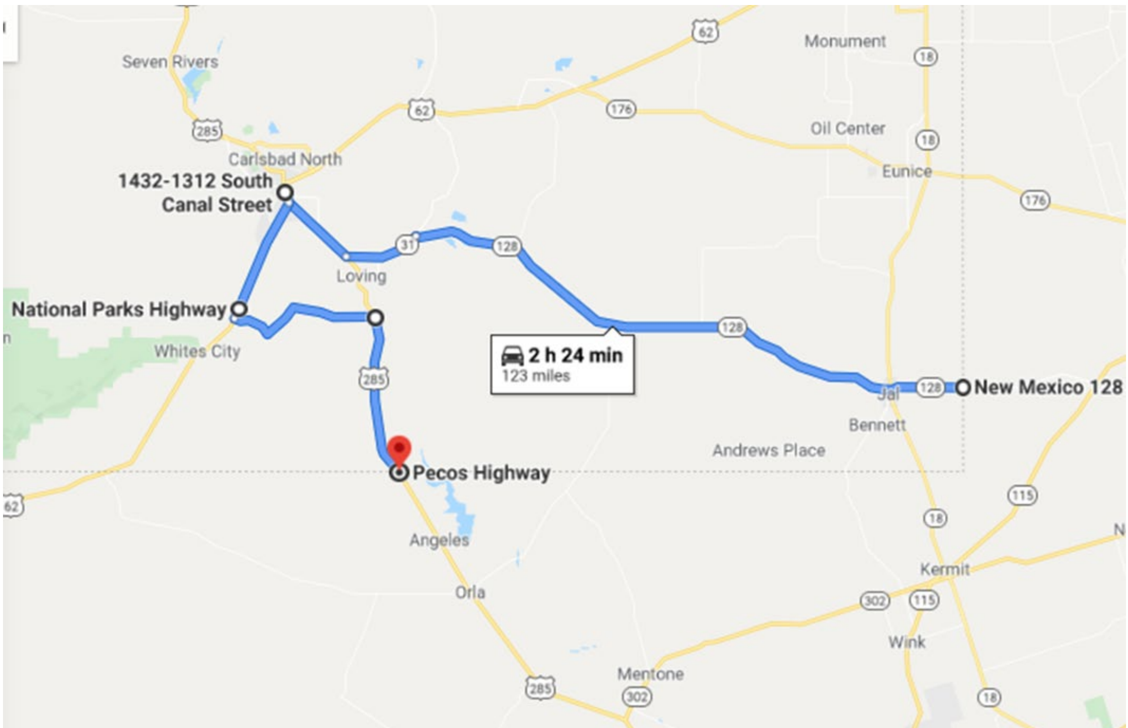

Figure 29. Permit load route for scenarios #8 through #10 (adapted from Google Maps).

2. TASK 2

DIRECT COMPARISON OF TOTAL FEES CHARGED ACROSS NEIGHBORING STATES

The primary objective of Task 2 is to assess the differences in fees charged for similar OS/OW load configurations and route types across Arizona, Colorado, Oklahoma, and Texas. The seven cases/scenarios identified in Task 1 and three additional cases/scenarios proposed by the NMDOT Bridge Bureau were used to quote permits from neighboring states. Overweight-vehicle-permit fees charged by the four states are compared to the fees charged by New Mexico to facilitate a clear comparison. This section of the report presents the basic assumptions and the methodology used to obtain the permit quotes. In addition to collecting permit cost information, the research team also discusses hypothetical permit fee adjustments to illustrate the potential impacts in bringing New Mexico on par with neighboring states. A simple revenue impact is provided at the end of the section.

2.1. Basic assumptions

The following assumptions were made when obtaining each permit quote to avoid additional fees and taxes:

- Loads were nonreducible/indivisible
- Proper registration and licenses were obtained for each vehicle
- Loads were specifically described (self-propelled, oil rig, crane, pump, drill etc.)

Permits procured in the five states are strictly for travel on state and interstate highways. Routes that require travel on local or county roads may need approval and permittance from the city or county of travel.

Arizona has two main classes of permits; one class has a flat fee while the other has a flat fee with an additional fee for an engineering analysis based on the total hauling distance. When obtaining permit costs by phone, the specialists/customer representatives typically asked for vehicle dimensions (e.g., loaded length, width, height, axle spacings); weights (e.g., GVW, axle weights) and route (e.g., coordinates, addresses) to provide a quote. Instead, David Medlin (ADOT, Class A Permit Customer Service Representative) and Chris Pippin (ADOT, Class C Supervisor) explained the permitting costs and did not take any vehicle information to give the quotes like the permitting office staff had done in other states. Therefore, actual permit costs in Arizona for all cases may significantly deviate from reported values.

2.2. Methodology

2.2.1. *Route selection*:

NM routes for cases 1 through 7 were selected based on the statistical analysis conducted in Task 1. Routes for cases 8, 9 and 10 were provided by Jeff Vigil (NMDOT Bridge Management Engineer) and are representative of a high overweight vehicle traffic corridor in South-Eastern New Mexico. Route length, road type composition, and terrain were extracted in each case and used to guide the selection of similar routes in the states of Colorado, Oklahoma, and Texas (recall that ADOT permit customer service representatives did not provide vehicle and route specific quotes but rather referred the team to general permitting guidance). Google Maps was used to mark the start and end points (latitude and longitude) for each route during the permitting process.

Note that despite our efforts to match route attributes, the ultimate effect on permit cost is relatively minor as in certain cases overweight fees are assessed based on a flat rate regardless of route characteristics. In cases where mileage surcharges are assessed these do not depend on roadway characteristics; however, additional engineering analysis fees may be charged to ensure the route is permissible. Specific routes used to quote overweight permit fees can be found in Appendix B.

2.2.2 *Obtaining permits*:
Permits from the states of Colorado and Texas were obtained through their permitting websites COOPER and TXPros, respectively, with assistance from permitting office staff. Vehicles considered super heavy in the state of Texas were permitted using a document titled *Super Heavy Application Packet* (*SHAP*), provided by the Texas Department of Motor Vehicles (TxDMV) which contains information regarding super heavy vehicle classifications, the permitting process for those vehicles, and a breakdown of the fees assessed to said vehicles [8]. Permits obtained for Arizona and Oklahoma were obtained completely by phone directly from customer service representatives or other permitting office staff members.

2.2.3 *Permitting websites*:
Users of the TXPros and COOPER websites are prompted whether they need help determining what permit they need or know which permit they seek to purchase. If the user chooses guidance in determining their permit type, the user is asked several questions regarding the dimensions of the vehicle and gross vehicle weight (GVW). They are also asked if they will require a single trip or annual permit, and then the website selects a permit type based on the user's answers. If the user chooses to select the permit themselves, they are presented with a drop-down list of permit types they can chose from.

2.3. Summary of permit fees by case
As shown in Table 13, NM charges the lowest fees of all five states in all but one case (no. 5, where the lowest charging state is AZ, with an amount of $15.00). In six of the ten cases, OK is the highest charging state. Most of the fees charged by TX are above the five-state average and are the closest to OK. The fees charged by AZ and CO are more comparable to the current NM fees; however, overweight traffic demand in South Eastern New Mexico is closest to Texas and Oklahoma. In fact, Colorado does not even permit the super heavy load cases (nos. 3, 8, 9, and 10) as these exceed the state limits imposed on axle-group weights and would not be allowed across the state line.

Table 13. Permit fees by case for each state.

PERMIT INFORMATION			PERMIT FEE					
Case	GVW [lbs]	Route [mi]	AZ	CO	OK	TX	Avg.	NM
1	100,000	98	$ 75.00	$ 90.00	$ 240.00	$ 210.00	$ 131.33	$ 41.66
2	246,000	76	$ 280.00	$ 250.00	$ 1,800.00	$ 1,405.00	$ 782.32	$ 176.62
3	226,500	192	$ 570.00	-	$ 1,700.00	$ 1,405.00	$ 1,009.06	$ 361.24
4	90000	396	$ 75.00	$ 80.00	$ 200.00	$ 210.00	$ 121.56	$ 42.82
5	80000	371	$ 15.00	$ 30.00	$ 43.68	$ 60.00	$ 34.74	$ 25.00
6	72000	78	$ 75.00	$ 70.00	$ 43.68	$ 31.00	$ 48.94	$ 25.00
7	110000	42	$ 75.00	$ 80.00	$ 43.68	-	$ 59.02	$ 37.39
8	324100	123	$ 397.50	-	$ 2,521.00	$ 1,405.00	$ 1,178.49	$ 390.46
9	255000	123	$ 397.50	-	$ 1,830.00	$ 1,405.00	$ 979.18	$ 284.22
10	303950	123	$ 397.50	-	$ 2,319.50	$ 1,405.00	$ 1,120.37	$ 359.48

NOTE: NM charges the lowest fees of all five states in all but one case. CO does not permit super loads (cases 3, 8, 9, and 10); in TX, case 7 exceeds the axle load limits established in the automated permitting system.

We also were unable to obtain a quote from Texas for Case 7 because the specific axle-group weight configuration exceeded the state limits set on their automated permitting system (69,000 lbs. on a tandem axle). Unlike CO, NM, OK, and TX, Arizona did not provide actual permit quotes. Instead, the state permitting office provided guidance for the research team to calculate the permit fees.

2.4 Permit quotes by case

2.4.1. *Case 1*:

2.4.1.1 Routes:

The NM route, a total of 98 miles, for Case 1 traveled primarily on state highways, with a small segment on a US highway (see Figure 6). Routing in CO for Case 1 was done on the eastern side of the state because the topography is closest to Southern New Mexico's in that region of the state. For the same reason, routing in OK for this case was done in the southwest region of the state. The NM route for this case began at the TX-NM border, therefore, the TX route began at the same location in an attempt to ensure road conditions were as close to one another as possible. Routing was not necessary to obtain a permit quote in AZ, therefore a route was not identified in that state.

2.4.1.2 Permit cost

The cost for Case 1 to be permitted in NM is $41.66, and was computed with the following equation [9, 10]:

$$\boldsymbol{P = F + \frac{GVW - 86400\ lbs}{2000\ lbs} 0.025d} \qquad \text{Eq. 1}$$

where P is the permit cost ($), F is the overweight fee assessed to any vehicle with gross vehicle weight greater than 86,400 lbs ($25), GVW is the gross vehicle weight (lbs), and d is the mileage traveled by the vehicle (mi). In NM, if the GVW or the vehicle combination exceeds 26,000 lbs, an electronic Weight Distance Permit (WDP) is required by law [9]. If the driver fails to produce a valid and current WDP, a trip tax based on the miles to be operated in NM and the GVW will be assessed. The vehicle must also be properly registered in the listed jurisdictions of the vehicles International Registration Plan Cab Card, or fees will be assessed. Shipping papers or a bill of lading with information describing the transported load, the weight of the load, load consigner, load consignee, and load transporter must be included in the vehicle's documentation, or fees will be assessed [9]. The vehicle's driver must possess a current and valid commercial driver's license, or the driver will be placed out-of-service and may be cited and fined [9]. The vehicles record of duty status (log book) must be current up to the last change of duty status, and the Single State Registration System document for insurance and authority for states listed on the certificate must be included in the vehicles documentation, or fees may be assessed. If the vehicle is a special fuel powered vehicle and the driver fails to present a valid International Fuel Tax Agreement (IFTA) decal or license, a temporary special fuel permit fee of $5.00 will be assessed, and a special fuel tax of five cents ($.05) per mile will be assessed based on the miles traveled in NM [9].

The cost of permitting this vehicle in AZ, according to Medlin's [11] permit descriptions, would be $75.00, and is independent of mileage. The permit cost for Case 1 is $90.00 in CO [12], and $210.00 in TX [13], which included a permit and weight fees of $75.00 and $135.00, respectively. The cost of permitting this vehicle in OK, according to Kim Hamilton (Permit Clerk/Customer Service Representative) was $240.00, and it was independent of mileage [14].

2.4.2. *Case 2*:

2.4.2.1 Routes:
In Case 2, the NM route travels 76 miles along US highways for the majority of the route and ends on a small segment of state highways (see Figure 10). Routing in CO for Case 2 was also done on the eastern side of the state since the topography is closest to that in southern New Mexico. For the same reason, routing in OK for this case was done in the southwest region of the state. Because this vehicle was considered super heavy in TX, and the vehicle's route would need to be analyzed and approved by an engineer, a route was not specified. Routing was not necessary to obtain a permit quote in AZ, therefore a route was not identified in that state.

2.4.2.2 Permit cost
The cost to permit this vehicle in NM was $176.62, calculated using Eq. 1. The permit cost for this vehicle in AZ was $280.00 according to Pippin's [15] description of the Class C permits, which included a $90 permit fee and a state bridge analysis fee of $125.00 per every 50 mi increment of the route. In this case, the state bridge analysis fee would be $190.00. In CO, the cost of permitting this vehicle was $250, the fee for a Chapter 6 Special permit [12]. The fee for permitting this vehicle in OK was $1,800.00 [14]. The cost for permitting this vehicle using the *SHAP* in TX was $1,405.00, which includes an initial permit request fee of $435.00, a final permit request fee of $470.00, and if the vehicle crosses bridges and/or is over 800,000 lbs. a fee of $500.00 is assessed, or if the vehicle does not cross bridges and/or is less than 800,000 lbs. a fee of $100.00 is assessed [13]. In this case, a $500 engineering fee was included because it was assumed the vehicle would cross a bridge on a 76-mile trip.

2.4.3. *Case 3*:

2.4.3.1 Routes:
The route for Case 3 in NM traveled along a state highway for a short distance and continued on interstate highways for the remainder of the 192 miles traveled (see Figure 13). The route in OK for this case traveled a similar route along similar types of roads in southwest Oklahoma. Routes for Case 3 in AZ and TX were not identified because the vehicle was not permittable without an engineering analysis due to its dimensions and axle weights. This vehicle could not be permitted in the state of CO because of its axle weights and dimensions.

2.4.3.2 Permit cost
In NM, the cost to permit this vehicle was $361.24 based on Eq. 1. In AZ, the permit cost was $570.00 according to Pippin's [15] description of the Class C permits, which includes a $90 permit fee and a state bridge analysis fee of $480.00. In OK, the permit fee was $1,700.00 [14]. It was stressed that this quote was an estimate and may not reflect the true cost of the permit because the engineering analysis fee could only be assessed after the analysis was completed and changes to the route, a request to change vehicles, or non-permittance may occur. For the purpose of this study, engineering analysis costs in OK were not considered nor obtained. The TX permit cost for this case was determined using the *SHAP*, and was $1,405.00, assuming the vehicle crossed bridges and an engineer bridge analysis fee of $500.00 would be assessed [13].

2.4.4. *Case 4*:

2.4.4.1 Routes:
The NM route for Case 4 solely travels on an interstate highway for 396 miles (see Figure 17). As such, all routes in the other states travel along interstate highways. The original NM route

crossed the NM-TX border on I-40, but because of restrictions in route length, the TX route could not start on I-40 and instead was located along I-10 in southern TX. Because of length restrictions and road type, the OK route for this case was only 376 miles long which had no effect on the permit cost. The CO route could not be restricted to the eastern side of the state because of length restrictions and the route travels through mountainous terrain. This did not affect the cost of the permit, but the terrain is significantly different.

2.4.4.2 Permit cost
The NM permit cost for Case 4 was $42.82 based on Eq. 1. According to the explanations given by Medlin [11], the permit cost for this vehicle in AZ was $75.00. The permit fee for this vehicle in CO was $80.00, which includes only the OS/OW permit fee [12]. The permit cost for this OS/OW case in OK was $200.00 [14]. The cost for this permit in TX was $210.00, which included a $75.00 permit fee and a $135.00 weight fee [13].

2.4.5. *Case 5*:

2.4.5.1 Routes:
The NM route for Case 5 solely travels on an interstate highway for 371 miles (see Figure 21). As such, all routes in the other states travel along interstate highways. The NM route begins at the NM-TX border, but because of restrictions in route length, the TX route could not start at the same location and was located along an interstate in southern TX. Because of length restrictions and road type, the OK route for this case was only 357 miles long which had no effect on the permit cost. The CO route could not be restricted to the eastern side of the state because of length restrictions and the route travels through mountainous terrain. This did not affect the cost of the permit, but the terrain is significantly different.

2.4.5.2 Permit cost
The NM permit cost for Case 5 was $25.00 because its GVW was less than 86,400 lbs. and no additional weight fees were assessed [9]. According to the explanations given by Medlin [11], the permit cost for this vehicle in AZ was $15.00. The permit fee for this vehicle in CO was $30.00, which includes only the OS permit cost [12]. The permit cost for this OS case in OK was $43.68 [14]. The permit cost in TX was $60.00, which only included the permit fee [13].

2.4.6. *Case 6*:

2.4.6.1 Routes:
The route for Case 6 in NM traveled a total of 78 miles, most of which were on state highways with a short distance traveled on a US highway (see Figure 25). The NM-route started at the NM-TX border; therefore, the TX route began at the same location in an attempt to maintain similar road conditions from one route to the other. The routes in CO and OK were located in portions of the states where the topography was similar to that in southern NM.

2.4.6.2 Permit cost
In NM this vehicle was permitted as an oversized vehicle with a $25.00 permit fee because the length of the vehicle exceeded the maximum length for the vehicle type [9]. The permit cost in AZ was $75.00, the cost for a self-propelled vehicle permit [11]. The permit fee for this case in CO was $70, the fee for an OS vehicle [12]. The permit fee in OK was $43.68 for a special purpose vehicle traveling on US and state highways [14]. The permit fee in TX for this vehicle was $31.00 and was dependent on mileage [13]. See permit quote in Appendix B.

2.4.7. *Case 7*:

2.4.7.1 Routes:
The NM route of 42 miles for Case 7 traveled solely on state highways (see Figure 28) and as such, routes identified for CO and OK were located only on state highways. This particular vehicle configuration was not able to be permitted in TX because of its axle weights and configuration.

2.4.7.2 Permit cost
The permit in NM for Case 7 cost $37.39 according to Eq. 1. The permit cost in AZ was $75.00 because it was a self-propelled vehicle [11]. The permit fees in CO were $80.00 for an OS/OW vehicle [12]. See the permit quote in Appendix B. The fees for permitting in OK was $43.68 because it was a special purpose vehicle traveling only on US and state roads [14]. A permit in TX could not be obtained for this vehicle because the dimensions and axle weights were not within the permitting guidelines.

2.4.8. *Case 8*:

2.4.8.1 Routes:
The NM route of 123 miles for Case 8 was provided by Jeff Vigil (NMDOT Bridge Management Engineer) and was also used as the NM routes for Cases 9 and 10 (see Figure 29). The route traveled on both state and US highways. The only route necessary for obtaining permit quotes for this case was in OK, and the route also travels along state and US highways. This vehicle was not permittable in CO due to its axle weights and configuration.

2.4.8.2 Permit cost
The permit fee for Case 8 in NM was $390.46 based on Eq. 1. The permit cost for this case in AZ was $397.50, which includes an engineering analysis fee of $307.50 [15]. The fee in OK was $2,521.00, and it was stressed that this quote was an estimate and may not reflect the true cost of the permit because the engineering analysis fee could only be assessed after the analysis was completed and changes to the route, a complete change in vehicle, or non-permittance may occur [14]. The permit fee in TX was $1,405.00 in accordance with the *SHAP*, and assuming the vehicle would cross bridges on the 123-mile route through TX [13].

2.4.9. *Case 9*:

2.4.9.1 Routes:
The NM route for Case 9 was provided by Jeff Vigil (NMDOT Bridge Management Engineer) and was also used as the NM routes for Cases 8 and 10. The route traveled on both state and US highways. The only route necessary for obtaining permit quotes for this case was in OK, and the route also travels along state and US highways. This vehicle was not permittable in CO due to its axle weights and configuration.

2.4.9.2 Permit cost
The NM permit fee for this vehicle was $284.22 according to Eq. 1. The AZ permit cost was $397.50, including an engineering analysis fee of $307.50 [15]. The permit fee for this case in OK was $1,830.00, and it was stressed that this was merely an estimate and may not reflect the true cost of the permit because the engineering analysis fee could only be assessed after the analysis was completed [14]. The permit fee in TX was $1,405.00 in accordance with the *SHAP*, and assuming the vehicle would cross bridges on the 123-mile route through TX [13].

2.4.10. *Case 10*:

2.4.10.1 Routes:
The NM route for Case 10 was provided by Jeff Vigil (NMDOT Bridge Management Engineer) and was also used as the NM routes for Cases 8 and 9. The route traveled on both state and US highways. The only route necessary for obtaining permit quotes for this case was in OK, and the route also travels along state and US highways. This vehicle was not permittable in CO due to its axle weights and configuration.

2.4.10.2 Permit cost
In NM the permit cost for this vehicle was $359.48, as per Eq. 1. The permit cost in AZ was $397.50, including an engineering analysis fee of $307.50 [15]. The permit fee for this case in OK was $2,319.50 and it was stressed that this was merely an estimate and may not reflect the true cost of the permit because the engineering analysis fee could only be assessed after the analysis was completed [14]. The permit fee in TX was $1,405.00 in accordance with the *SHAP*, and assuming the vehicle would cross bridges on the 123-mile route through TX [13].

2.5. Hypothetical permit fee adjustments and simplified revenue analysis

The survey of permit costs across neighboring states indicates that New Mexico is charging either the least (9 cases), or well below average permit fees (1 case). In this section, permit quotes for the different cases and permit revenue data are used to explore the economic impact of changes in permit costs on the state revenues from overweight fees.

In a revenue neutral permit fee structure the ultimate objective of the overweight fees is to recover sufficient funds to mitigate the damage caused by overweight vehicles to state roads, bridges and other transportation infrastructure, to recover the administrative costs associated with permit processing, and the costs of compliance monitoring (i.e., weigh-in-motion stations, instrumented bridges and roadways, etc.). Quantifying permit processing and compliance monitoring costs is straight forward. However, assessing infrastructure damage related costs is not. For instance, the incremental damage to a pavement structure that an overweight vehicle causes, relative to that of a vehicle under the legal weight limit, not only depends on the magnitude and frequency of the load and the load configuration, but also on the pavement structure itself, its current physical state under service, and the prevailing environmental conditions.

In the absence of damage assessment, state departments of transportation are faced with the challenge of setting appropriate overweight permit fees without guidance from mechanistic means. The wide range in assessed fees presented in Table 13 illustrates the struggle. Clearly, the infrastructure characteristics (interstate highway pavement structures for instance) across Oklahoma and Arizona are not different enough to justify a 10-fold difference in permit fee for the same vehicle (case 10, for example). After all, both states use similar design methods, construction materials and processes, and quality control measures.

Foregoing actual damage assessment, the data collected as part of this project so far can still be useful in moving the state towards securing enough funds to maintain and replace infrastructure affected by overweight vehicle traffic. The hypothetical permit fee adjustments (HPFAs) provided below are solely based on statistical data.

2.5.1 HPFA 1: Increase the base single trip permit fee.
The average number of single trip permits per month issued by New Mexico since January 2015 ranges between 4,500 and 7,200 permits/month (note that this information was provided

in a spreadsheet by the permitting office that included also revenue). Thus, a change in the single trip OS/OW fee from $25 to $50 can bring New Mexico up closer to the average of the four neighboring states (see cases 5, 6, and 7), and result in an increase in revenue between $1.4 million and $2.2 million per year from the flat single trip permits.

2.5.2 HPFA 2: Increase the annual permit fee.

Increasing the single trip permit fee without adjusting the annual permit fee would only encourage operators to purchase annuals. Annual permits in Arizona, Colorado, Oklahoma and Texas range from $400 to $4,000. The average number of annual permits per month issued by New Mexico since January 2015 ranges between 580 and 870 permits/month. Increasing the annual permit fee (currently $250) in New Mexico to about $1,000 would be in line with the neighboring state prices and bring in an additional $5.2 million to $7.8 million per year from annual trip permits. Annual permits should be capped by gross vehicle weight and by axle weight and should be assessed an additional fee for the number of miles traveled while over the established limits.

2.5.3 HPFA 3: Increase the mileage-based surcharge for vehicles exceeding GVW.

Excess gross vehicle weight (EGVW) surcharges are already assessed by New Mexico on vehicles seeking to transport loads over 86,400 lbs. at a rate of $0.025 per ton/mile. The excess gross vehicle weight mileage surcharge is instrumental in a damage-based fee assessment structure; however, at its current rate it is clearly not being used effectively (see the New Mexico fees compared to the averages in cases 2, 3, 8, 9, and 10). The New Mexico Department of Transportation needs to have the flexibility to adjust the rate to better respond to changes in overweight vehicle traffic patterns.

2.5.2 HPFA 4: Assess a mileage-based surcharge for vehicles exceeding axle weight.

In general, excess axle weight (EAW) is more deleterious to pavements than EGVW. Assessing a linear or an exponential mileage over-axle surcharge per axle, would ensure funds are collected from vehicles with GVW under 86,400 lbs. (the current cut off for over-weight mileage surcharge). Furthermore, a steep mileage EAW surcharge would also encourage overweight vehicle operators to employ vehicles with axle load configurations that are less detrimental to pavement structures in the state. For these reasons, the state should consider instituting an EAW mileage surcharge.

EGVW and EAW mileage surcharges could be fined tuned to yield permit costs that better resemble the costs of mobilizing similar loads in Texas and Oklahoma. The two parameters would also offer a significant level of flexibility to implement revisions to the permitting fees based on quantifiable damage to transportation infrastructure in the state. In the interim, an increase in the EGVW mileage surcharge to $0.1/ton·mile and the addition of a $0.05/ton·mile EAW surcharge would help bring the super load permit fees in par with the fees charged by Texas and Oklahoma. Table 14 shows the combined impact of recommendations 1, 3 and 4 on New Mexico's OS/OW fees for the 10 cases studied.

Table 14. Combined impact of increasing the flat single trip permit fee to \$50, increasing the excess gross vehicle weight mileage surcharge to \$0.1/ton·mile, and of adding a \$0.05/ton·mile excess axle weight surcharge.

PERMIT INFORMATION			PERMIT FEE ANALYSIS					
Case	GVW [lbs]	Route [mi]	EGW (lb)	EAW (lb)	NM fee	4 state avg.	OK-TX median	Proposed NM fee
1	100,000	98	13,600	12,900	\$ 41.66	\$ 153.75	\$ 225.00	\$ 148.25
2	246,000	76	159,600	72,000	\$ 176.62	\$ 933.75	\$ 1,602.50	\$ 793.28
3	226,500	192	140,100	66,100	\$ 361.24	\$ 1,225.00	\$ 1,552.50	\$ 1,712.24
4	90000	396	3,600	7,800	\$ 42.82	\$ 141.25	\$ 205.00	\$ 198.50
5	80000	371	-	-	\$ 25.00	\$ 37.17	\$ 51.84	\$ 50.00
6	72000	78	-	15,000	\$ 25.00	\$ 54.92	\$ 37.34	\$ 79.25
7	110000	42	23,600	35,900	\$ 37.39	\$ 66.23	\$ 43.68	\$ 137.26
8	324100	123	237,700	130,200	\$ 390.46	\$ 1,441.17	\$ 1,963.00	\$ 1,912.22
9	255000	123	168,600	44,000	\$ 284.22	\$ 1,210.83	\$ 1,617.50	\$ 1,222.19
10	303950	123	217,550	122,600	\$ 359.48	\$ 1,374.00	\$ 1,862.25	\$ 1,764.93

3. TASK 3 (PAVEMENTS)

OW TRANSPORTATION INFRASTRUCTURE DAMAGE ANALYSIS

Increasing traffic demand has been associated to increases in congestion, highway maintenance costs, frequency of required roadway replacement, air pollution, fuel consumption, and travel times for road users [19]. The impacts of oversize/overweight (OS/OW) vehicles have been the subject of numerous state and national legislative sessions. Challenges faced by states related to these types of vehicles include those related to roadway preservation, capacity, safety, environment, industry productivity, and economic impact [32].

The transportation industry is vital to specific businesses, including the timber industry, farming and agriculture, oil and gas, and many others. In each case, axle configuration and loading are governed by the specific characteristics of the goods transported. The New Mexico Department of Transportation (NMDOT) routinely issues oversize (OS) and overweight (OW) permits for the transport of non-divisible payloads that exceed the legal size or weight limits allowed on the state highway network. The fees assessed for such permits are primarily meant to cover administrative costs incurred by the permitting office and are not necessarily meant to cover transportation infrastructure consumption and highway maintenance.

3.1. Task objective

The primary objective of this task is to collect the information necessary to conduct a technical analysis of damage induced by overweight traffic to the state's infrastructure. For this purpose, the research team has conducted a review of the literature to identify relevant methods employed in the analysis of damage to pavement structures. Pavements are designed to accumulate damage overtime under cyclic traffic loading. Thus, failures are insidious rather than catastrophic. As the pavement deforms under traffic loading, the magnitudes of strains and stresses that develop within the different layers can be used as predictors of the pavement life; that is, the number of cycles to failure. Stresses and strains are a function of the loading magnitude and axle configuration, and of the material properties and dimensions of the pavement layers. Environmental conditions are known to alter the mechanical properties of pavement materials (e.g., temperature and moisture content), which also change as the pavement deteriorates. Therefore, accurately quantifying the damage caused by any given vehicle is rather complex.

Each of the methods presented in this section makes use of simplifying assumptions to constrain the problem so that damage can be estimated. Each method also requires specific information about the axle load configuration and the pavement structure. Understanding information requirements is critical in the development of a suitable framework of analysis. If the information needed is already collected and curated, the implementation of the damage assessment can be straight forward. However, if information gaps exist, a plan will be needed to obtain it.

3.2. Pavement damage assessment methods

3.2.1 Fixed vehicle analysis

In the fixed vehicle analysis, the damage caused by a given axle-load configuration is normalized by the damage caused by a standard axle. The most common fixed vehicle analysis method in existence is used by the AASHTO pavement design [16][26]. The standard axle is the 18-kip (80-kN) single-axle load. The damage caused by any other axle load is determined using its corresponding equivalent axle load factor (EALF), and reported in terms of the number of equivalent single axle loads (ESAL). EALFs can be obtained for different load magnitudes and axle configurations according to:

$$EALF = \frac{W_{t18}}{W_{tx}} \quad \text{Eq. 2}$$

where W_{t18} is the number of 18-kip single axle load applications to time t and W_{tx} is the number of x-axle load applications at the end of time t.

$$log(W_{tx}/W_{t18}) = 4.79\, log(18+1) - 4.79\, log(L_x + L_2) + 4.33\, log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad \text{Eq. 3}$$

where L_x is the load in kips on one single axle, one set of tandem axles, or one set of tridem axles and L_2 is the axle code (1 for single axle, 2 for tandem axles, 3 for tridem axles, and 4 for quad axles). G_t and β_x are given by the following equations (note that β_{18} is the value of β_x that corresponds to the 18-kip single standard axle):

$$G_t = log(\frac{4.2 - p_t}{4.2 - 1.5}) \quad \text{Eq. 4}$$

$$\beta_x = 0.4 + \frac{0.081(L_x + L_2)^{3.23}}{(SN+1)^{5.19} {L_2}^{3.23}} \quad \text{Eq. 5}$$

where SN is the structural number that captures the pavement structure dimensions and material properties, and p_t is the terminal serviceability. Under heavy axle loads (EALF > 1), the EALF increases as p_t or SN decreases.

The AASHTO fixed vehicle analysis offers a relatively simple means of assessing the relative damage caused by different axle-load configurations. The use of representative SN and p_t values facilitate the development of network level EALFs with relatively little information. However, damage estimates based on the empirical relationships are not expected to be very accurate, particularly when applied to non-conventional axle configurations.

3.2.2 Modified equivalent axle load factors

Over time, new methods have been developed to improve the quality of the EALF estimates and to provide more flexibility in terms of axle-load configurations. An example of a modified ESAL equation is presented next [31]:

$$EALF = k(\frac{p_x}{p_{80}})^{\alpha} \quad \text{Eq. 6}$$

where p_x is the axle or axle-group load, p_{80} is the load of the standard axle, α is a coefficient to capture the distress mode (e.g., fatigue cracking, rutting), and k is given by:

$$k = 254.03 \times (E_{sub})^{0.033393} \times (H_{bet})^{-1.0416} \times e^{-1.2928 \times AP} \quad \text{Eq. 7}$$

where E_{sub} is the resilient modulus of the subgrade, H_{bet} is the asphalt layer thickness in cm and AP is an axle configuration parameter (see Table 15). This modified EALF definition attempts to capture more directly the mechanical properties of the pavement layers.

Table 15. Values of parameter AP (see Equation 7)

Axle type	AP
Single-axle single-wheel	1
Single-axle dual-wheel	2
Tandem-axle single-wheel	3
Tandem-axle dual-wheel	4
Tridem-axle single-wheel	4.5
Tridem-axle dual-wheel	5.5

However, EALFs can also be defined specifically based on the mechanical response of the pavement in terms of stresses and/or strains under the axle load. In the case of flexible (i.e. asphalt) pavements, the two most common failure mechanisms are fatigue cracking and rutting. The asphalt institute as developed EALFs for the two failure mechanisms. The EALF based on the fatigue cracking criterion is given by:

$$EALF = (\frac{\varepsilon_{t\,x}}{\varepsilon_{t\,18}})^{3.29} \qquad \text{Eq. 8}$$

where ε_{tx} is the maximum tensile strain in the asphalt concrete layer caused by the x-axle and ε_{t18} is the maximum tensile strain in the asphalt concrete layer caused by the standard 18-kip axle. Similarly, the EALF can be defined in terms of the rutting failure criterion as follows:

$$EALF = (\frac{\varepsilon_{c\,x}}{\varepsilon_{c\,18}})^{4.47} \qquad \text{Eq. 9}$$

where ε_{cx} is the maximum compressive strain in the subgrade caused by the x-axle and ε_{c18} is the maximum compressive strain in the subgrade caused by the standard 18-kip axle.

By incorporating a measure of the actual mechanical response of the pavement structure, these modified EALFs offer a significantly more accurate means of estimating the damage caused by a specific axle compared to the standard axle. However, the traditional AASHTO equations cannot be used to estimate the required strains and stresses in the pavement structure. The actual mechanical performance of pavement structures is in the purview of fixed traffic analysis discussed in the next section.

3.2.3 Fixed traffic analysis

Fixed traffic analysis has been used in pavement design for airport runways or highways subjected to heavy wheel loads but low traffic volumes. In both cases, the priority is to determine the mechanical response of the pavement under the effect of the specific load [26]. Traditionally, the analysis was based on closed-form solutions of idealized pavement structures which presented significant limitations. With advances in numerical simulation and constitutive modeling, fixed traffic analysis can be conducted without the need for simplified geometries and material properties. The information requirements vary depending on the constitutive model selected for each material. At minimum, the analysis requires the thickness of each pavement layer and the material properties necessary for their respective constitutive models. These can be as simple as two elastic constants per layer in isotropic linear elastic models to several parameters and constitutive relations in more complex anisotropic non-linear elastoplastic or visco-elastoplastic models [24][30][23]. In fact, one of the primary challenges in the assessment of damage via numerical simulation is the determination of the mechanical parameters and the calibration of the models. Nonetheless, it has been shown that even when using the simplest isotropic linear elastic constitutive model, the resulting damage analysis offers an improvement over empirically obtained EALFs because it is able to capture site specific material responses [17].

An example procedure for conducting fixed traffic analysis using numerical simulations is presented in Figure 30. As shown, axle loads can be collected using Weigh-In-Motion (WIM) stations to develop an axle load spectra database. The material properties and thicknesses of the pavement layers can be determined non-destructively in the field using Ground Penetrating Radar (GPR) and Falling Weight Deflectometer (FWD). The recovered data provides the necessary information to simulate the different pavement layers in ABAQUS ® (a general finite element analysis software, see Figure 31). The results of the simulations provide the critical tensile and compressive strains as well as the vertical deflections which are used to determine the equivalent axle load factors for the different failure criteria (see Figure 32). The parameters collected using this approach offer the advantage of capturing the current physical state of the pavement, as supposed to the initial state of the pavement just after construction. Novel characterization methods and data processing using artificial intelligence are currently under development to speed up the data collection process and to reduce its labor intensiveness [33][25][28][20][22][21][29].

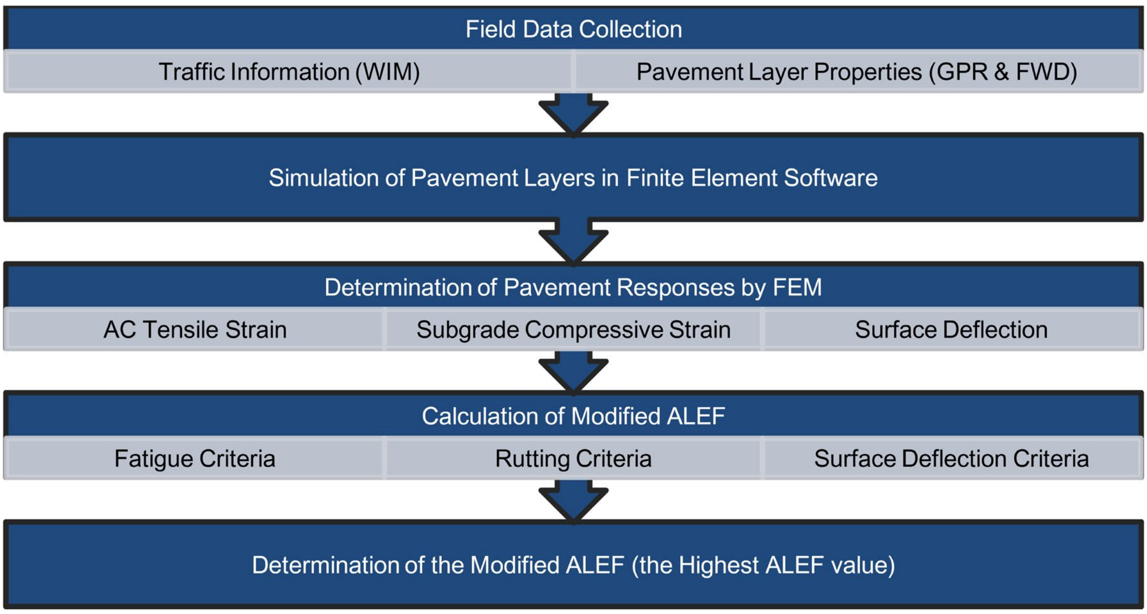

Figure 30. Example procedure for computing modified axle load equivalency factors [17].

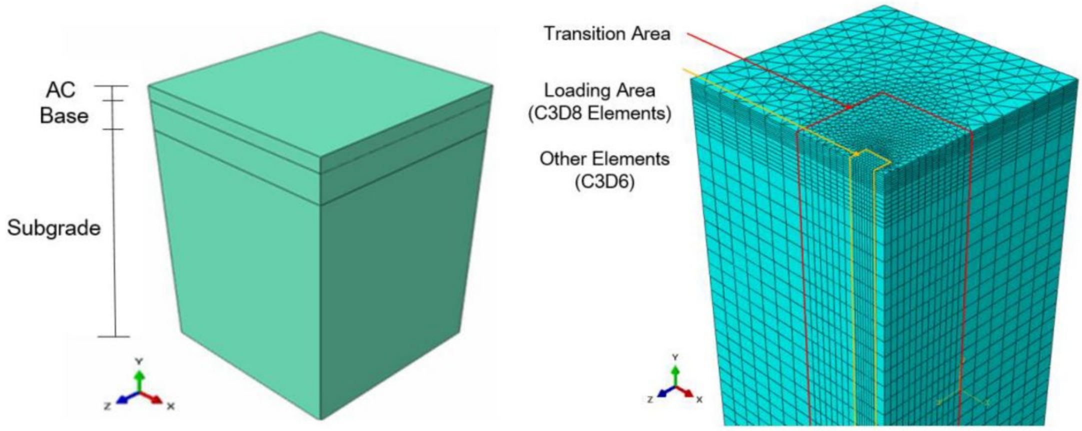

Figure 31. Model geometry (left) and discretization mesh (right) of flexible pavement structure in ABAQUS [17].

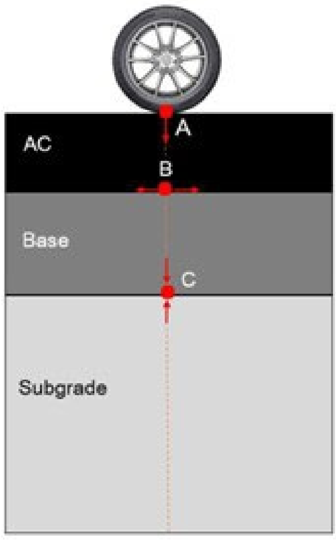

Figure 32. Locations of critical mechanical performance parameters in flexible pavement structure: (A) maximum surface deflection, (B) critical tensile strains in the asphalt concrete layer, and (C) maximum compressive strains in the subgrade layer. Modified from [17].

In flexible pavements the analysis considers failure due to fatigue cracking and rutting. The critical mechanical parameters are: (A) the maximum surface deflection; (B) the maximum tensile strain within the asphalt concrete layer; and (C) the maximum compressive strain within the subgrade. EALFs are derived for each failure criterion as follows.

EALF based on the fatigue failure criterion: the critical tensile strain occurs at the interface between the asphalt concrete and the base layer. Thus, the fatigue life of the pavement is governed by the tensile strain at the bottom of the asphalt layer. The number of cycles to failure at a given tensile strain amplitude is given by:

$$N_f = 7.96 \times 10^{-2}(\varepsilon_t)^{3.29}(E_{AC})^{0.85} \quad \text{Eq. 10}$$

where the N_f is the allowable number of load applications to fatigue failure, ε_t is the tensile strain at the bottom of asphalt layer, and E_{AC} is the Young's modulus of the asphalt layer. The

EALF for axle load group x compared to standard 18-kip axle based on the fatigue criterion can be calculated from equation 11:

$$EALF = (\frac{W_{t18}}{W_{tx}}) = (\frac{\varepsilon_{tx}}{\varepsilon_{t18}})^{3.29} \qquad \text{Eq. 21}$$

where ε_{tx} is the maximum tensile strain in the asphalt concrete layer caused by the x-axle, and ε_{t18} is the maximum tensile strain in the asphalt concrete layer caused by the standard 18-kip axle.

EALF based on the rutting failure criterion: The rutting failure model assumes that the asphalt layer does not experience any permanent deformation; therefore, all plastic deformations are associated with the subgrade performance [18]. In this case, the compressive strain ε_c on top of the subgrade is assumed to be the controlling mechanical parameter. The number of cycles to failure at a given compression strain (ε_c) amplitude is given by:

$$N_f = 1.37 \times 10^{-9}(\varepsilon_c)^{4.47} \qquad \text{Eq. 32}$$

The EALF for the rutting failure mode is given by:

$$EALF = (\frac{W_{t18}}{W_{tx}}) = (\frac{\varepsilon_{cx}}{\varepsilon_{c18}})^{4.47} \qquad \text{Eq. 43}$$

where $\varepsilon_{c\,x}$ is the maximum compressive strain in the subgrade caused by the x-axle and ε_{c18} is the maximum compressive strain in the subgrade caused by the standard 18-kip axle.

EALF based on the surface deflection criterion: Pavements can exhibit rutting even when there is no excessive permanent deformation on the subgrade. In these cases, the pavement failure is due to the accumulation of plastic deformations within the asphalt and base layers. The surface deflection failure criterion considers the maximum surface deflection under the axle loading as an index of the cumulative damage incurred by the pavement under its load. The number of cycles to failure according to this failure criterion is given by:

$$N_f = (\frac{1}{D})^{3.8} \qquad \text{Eq. 54}$$

where D is the magnitude of the maximum surface deflection caused by the single axle load. The EALF can be calculated using the following equation for single axle loads:

$$EALF = (\frac{W_{t18}}{W_{tx}}) = (\frac{D}{D_b})^{3.8} \qquad \text{Eq. 65}$$

where D_b is the surface deflection caused by the standard 18-kip single axle load. For load configurations using multiple axles in a group, the EALF is calculated according to the following equation:

$$EALF = (\frac{W_{t18}}{W_{tx}}) = (\frac{D}{D_b})^{3.8} + \sum(\frac{\Delta_i}{D_b})^{3.8} \qquad \text{Eq. 76}$$

where Δ_i represents the difference in magnitude between the maximum deflection calculated under each successive axle and the intermediate deflection between axles [27].

The center for transportation infrastructure systems at the University of Texas at El Paso recently conducted a fixed traffic analysis to develop modified damage equivalency factors and the remaining life analysis of representative pavement sections in the San Antonio, Corpus Christi, Yoakum, and Laredo Districts in Texas [17]. Field collected data from WIM stations, GPR and FWD tests were used to obtain the input parameters required for a 3D finite element model. Numerical simulations were used to estimate critical input parameters in the modified EALF models. The study compared the EALFs obtained from the mechanistic analysis to those obtained using the empirical AASHTO equations (see Figure 33). It was found that the empirical EALFs underestimate the damage caused by overweight vehicles. Furthermore, EALFs calculated based on FWD data collected over the summer where consistently higher than those calculated based on FWD data collected over winter.

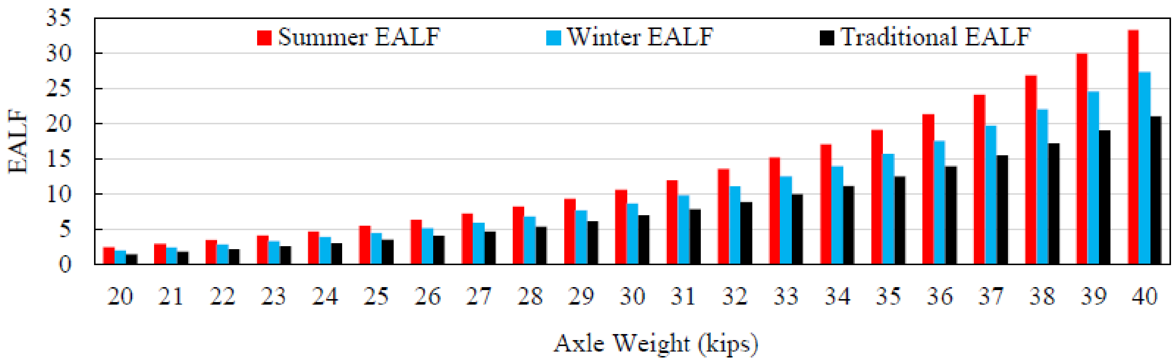

Figure 33. Differences in mechanistically determined equivalent axle load factors (EALFs), red and blue bars, and empirical (AASHTO) EALFs. Data presented for single axle loads (modified after [17]).

3.3. Equivalent single axle load factors for the most common overweight vehicles in the state of New Mexico

The determination of equivalent single axle load factors is a critical step in the development of a damage based overweight permit fee structure. In this section we use the AASHTO empirical equations to estimate the damage-based equivalencies between the different axle configurations and loadings that characterize the most common overweight vehicles identified earlier in the project as part of Task 1. In each case, a base truck ESAL is calculated by adding the EALFs for each legal axle or axle-group. This is used as the standard for comparison. The ESAL for the actual overweight truck is computed by adding the EALFs for each axle or axle-group. If any axle or axle-group loading in the overweight vehicle falls below legal, the legal axle group ESAL is used instead. EALFs in all cases are calculated assuming a structural number $SN = 5$ and a terminal serviceability index $p_t = 2.5$. The selected parameters correspond to the typical design of a flexible pavement structure in a Class V Traffic road (rural interstate or principal arterial highways).

3.3.1 EALF calculation

Equivalent single axle load factors are computed for each axle-group according to the equations presented in section 3.2.1. Here, the calculations for case 1 are presented step by step as an example. The most important pieces of information in the determination of the EALFs using the AASHTO fixed vehicle equations are the axle-configuration and the load in each of the axle-groups. The axle configuration and loading for case 1 are presented in Table 16.

Table 16. Loading configuration for Case 1.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*13,000*	*13,000*	*21,600*	----
2	Tandem	*2*	*18,600*	*37,200*	*35,100*	*2,100*
		2	*18,600*			
3	Tridem	*3*	*16,600*	*49,800*	*39,000*	*10,800*
		3	*16,600*			
		3	*16,600*			

Equivalent axle load factors are computed using the reported axle-group weights ($EALF_{\text{overweight}}$) and the axle-group weight limit ($EALF_{\text{legal}}$). Note that the steering axle (group 1) is below the legal axle weight limit. To calculate the damage contribution of the steer axle to the $EALF_{overweight}$ we use the legal weight limit (21,600 lbs.) instead of the actual axle weight (13,000 lbs.). Using the actual axle weight would result in a "damage credit" since the axle would cause less damage than the legal axle weight limit.

Group 1. Steering axle (single)

Since the axle weight is below the axle weight limit: $EALF_{\text{overweight}} = EALF_{\text{legal}}$

$$G_t = log(\frac{4.2-p_t}{4.2-1.5}) = log(\frac{4.2-2.5}{4.2-1.5}) = -0.2$$

$$\beta_x = 0.4 + \frac{0.081(L_x+L_2)^{3.23}}{(SN+1)^{5.19}{L_2}^{3.23}} = 0.4 + \frac{0.081(21.6+1)^{3.23}}{(5+1)^{5.19}1^{3.23}} = 0.575$$

$$\beta_{18} = 0.4 + \frac{0.081(18+1)^{3.23}}{(5+1)^{5.19}1^{3.23}} = 0.5$$

$$log(W_{tx}/W_{t18}) = 4.79\, log(18+1) - 4.79\, log(21.6+1) + 4.33\, log(1) + \frac{-0.2}{0.575} - \frac{-0.2}{0.5} = -0.308$$

$$\frac{W_{tx}}{W_{t18}} = \frac{1}{EALF} = 10^{-0.308}$$

$$EALF = 2.03$$

Group 2: Tandem axle

$EALF_{\text{overweight}}$ (37,200 lbs.)

$$G_t = log(\frac{4.2-p_t}{4.2-1.5}) = log(\frac{4.2-2.5}{4.2-1.5}) = -0.2$$

$$\beta_x = 0.4 + \frac{0.081(L_x+L_2)^{3.23}}{(SN+1)^{5.19}{L_2}^{3.23}} = 0.4 + \frac{0.081(37.2+2)^{3.23}}{(5+1)^{5.19}2^{3.23}} = 0.507$$

$\beta_{18} = 0.4 + \frac{0.081(18+1)^{3.23}}{(5+1)^{5.19}1^{3.23}} = 0.5$

$log(W_{tx}/W_{t18}) = 4.79\,log(18+1) - 4.79\,log(37.2+2) + 4.33\,log(2) + \frac{-0.2}{0.507} - \frac{-0.2}{0.5} = -0.198$

$\frac{W_{tx}}{W_{t18}} = \frac{1}{EALF} = 10^{-0.198}$

$EALF = 1.58$

$EALF_{legal}$ (35,100 lbs.)

$G_t = log(\frac{4.2-p_t}{4.2-1.5}) = log(\frac{4.2-2.5}{4.2-1.5}) = -0.2$

$\beta_x = 0.4 + \frac{0.081(L_x+L_2)^{3.23}}{(SN+1)^{5.19}L_2{}^{3.23}} = 0.4 + \frac{0.081(35.1+2)^{3.23}}{(5+1)^{5.19}2^{3.23}} = 0.489$

$\beta_{18} = 0.4 + \frac{0.081(18+1)^{3.23}}{(5+1)^{5.19}1^{3.23}} = 0.5$

$log(W_{tx}/W_{t18}) = 4.79\,log(18+1) - 4.79\,log(35.1+2) + 4.33\,log(2) + \frac{-0.2}{0.489} - \frac{-0.2}{0.5} = -0.097$

$\frac{W_{tx}}{W_{t18}} = \frac{1}{EALF} = 10^{-0.097}$

$EALF = 1.25$

Group 3: Tridem axle

$EALF_{overweight}$ (49,800 lbs.)

$G_t = log(\frac{4.2-p_t}{4.2-1.5}) = log(\frac{4.2-2.5}{4.2-1.5}) = -0.2$

$\beta_x = 0.4 + \frac{0.081(L_x+L_2)^{3.23}}{(SN+1)^{5.19}L_2{}^{3.23}} = 0.4 + \frac{0.081(49.8+3)^{3.23}}{(5+1)^{5.19}3^{3.23}} = 0.474$

$\beta_{18} = 0.4 + \frac{0.081(18+1)^{3.23}}{(5+1)^{5.19}1^{3.23}} = 0.5$

$log(W_{tx}/W_{t18}) = 4.79\,log(18+1) - 4.79\,log(49.8+3) + 4.33\,log(3) + \frac{-0.2}{0.474} - \frac{-0.2}{0.5} = -0.082$

$\frac{W_{tx}}{W_{t18}} = \frac{1}{EALF} = 10^{-0.082}$

$EALF = 1.21$

$\underline{EALF_{\text{legal}} \text{ (39,000 lbs.)}}$

$$G_t = log(\frac{4.2-p_t}{4.2-1.5}) = log(\frac{4.2-2.5}{4.2-1.5}) = -0.2$$

$$\beta_x = 0.4 + \frac{0.081(L_x+L_2)^{3.23}}{(SN+1)^{5.19}{L_2}^{3.23}} = 0.4 + \frac{0.081(39.0+3)^{3.23}}{(5+1)^{5.19}3^{3.23}} = 0.435$$
$$\beta_{18} = 0.4 + \frac{0.081(18+1)^{3.23}}{(5+1)^{5.19}1^{3.23}} = 0.5$$

$$log(W_{tx}/W_{t18}) = 4.79\,log(18+1) - 4.79\,log(39.0+3) + 4.33\,log(3) + \frac{-0.2}{0.435} - \frac{-0.2}{0.5} = -0.082$$

$$\frac{W_{tx}}{W_{t18}} = \frac{1}{EALF} = 10^{0.356}$$

$$EALF = 0.44$$

Combined EALFs:

The sum of the EALFs results in the equivalent 18-kip single axle loading (ESAL). That is, the damage caused by the permitted vehicle is equivalent to X-number of 18-kip single axle load passes, where X is the ESAL.

The total overweight equivalent single axle loading is given by:

$ESAL_{\text{overweight}} = 1_{\text{(steer)}} * 2.03 + 1_{\text{(Tandem)}} * 1.58 + 1_{\text{(Tridem)}} * 1.21 = 4.82$

The total legal equivalent single axle loading is given by:

$ESAL_{\text{legal}} = 1_{\text{(steer)}} * 2.03 + 1_{\text{(Tandem)}} * 1.25 + 1_{\text{(Tridem)}} * 0.44 = 3.72$

The normalized overweight equivalent single axle loading is given by:

$$\frac{ESAL_{overweight}}{ESAL_{legal}} = \frac{4.82}{3.72} = 1.30$$

The excess overweight equivalent single axle loading is given by:

$ESAL_{\text{overweight}} - ESAL_{\text{legal}} = 1.1$

Table 17. Summary of overweight and legal EALFs per axle group and combined for the load and axle configuration of the representative truck in Case 1 of Task 1.

Axle Type	Legal ESAL	Overweight ESAL
Steer	*2.03*	*2.03*
Tandem	*1.25*	*1.58*
Tridem	*0.44*	*1.21*
Total	***3.72***	***4.82***
Excess		***1.10***
Normalized	***1.00***	***1.30***

Tables 18 through 26 summarize the axle configurations and loads used in the calculation of the normalized EALF for the remaining 9 cases.

Table 18. Loading configuration for Case 2.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*18,000*	*18,000*	*21,600*	----
		3	*19,000*			
2	Tridem	*3*	*19,000*	*57,000*	*39,000*	*18,000*
		3	*19,000*			
		3	*19,000*			
3	Tridem	*3*	*19,000*	*57,000*	*39,000*	*18,000*
		3	*19,000*			
		3	*19,000*			
4	Tridem	*3*	*19,000*	*57,000*	*39,000*	*18,000*
		3	*19,000*			
		3	*19,000*			
5	Tridem	*3*	*19,000*	*57,000*	*39,000*	*18,000*
		3	*19,000*			

Table 19. Loading configuration for Case 3.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*20,000*	*20,000*	*21,600*	----
2	Tandem	*2* *2*	*22,000* *22,000*	*44,000*	*35,100*	*8,900*
3	Tandem	*2* *2*	*28,750* *28,750*	*57,500*	*35,100*	*22,400*
4	Tandem	*2* *2*	*26,250* *26,250*	*52,500*	*35,100*	*17,400*
5	Tandem	*2* *2*	*26,250* *26,250*	*52,500*	*35,100*	*17,400*

Table 20. Loading configuration for Case 4.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*12,000*	*12,000*	*21,600*	----
2	Tandem	*2* *2*	*20,000* *20,000*	*40,000*	*35,100*	*4,900*
3	Tandem	*2* *2*	*19,000* *19,000*	*38,000*	*35,100*	*2,900*

Table 21. Loading configuration for Case 5.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*12,000*	*12,000*	*21,600*	----
2	Tandem	*2* *2*	*17,000* *17,000*	*34,000*	*35,100*	*1,100*
3	Tandem	*2* *2*	*17,000* *17,000*	*34,000*	*35,100*	*1,100*

Table 22. Loading configuration for Case 6.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*18,000*	*18,000*	*21,600*	----
2	Tridem	*3* *3* *3*	*18,000* *18,000* *18,000*	*54,000*	*39,100*	*15,000*

Table 23. Loading configuration for Case 7.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Tandem	*2* *2*	*20,500* *20,500*	*41,000*	*35,100*	*5,900*
2	Tridem	*3* *3* *3*	*23,000* *23,000* *23,000*	*69,000*	*35,100*	*33,900*

Table 24. Loading configuration for Case 8.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*17,000*	*17,000*	*21,600*	----
2	Single	*1*	*17,000*	*17,000*	*21,600*	----
3	Quad	*4* *4* *4* *4*	*18,000* *18,000* *18,000* *18,000*	*72,000*	*42,900*	*29,100*
4	Quad	*4* *4* *4* *4*	*23,700* *23,700* *23,700* *24,500*	*95,600*	*42,900*	*52,700*
5	Tridem	*3* *3* *3*	*24,500* *24,500* *24,500*	*73,500*	*39,000*	*34,500*
6	Tandem	*2* *2*	*24,500* *24,500*	*49,000*	*35,100*	*13,900*

Table 25. Loading configuration for Case 9.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*20,000*	*20,000*	*21,600*	----
2	Quad	*4*	*15,000*	*60,000*	*42,900*	*17,100*
		4	*15,000*			
		4	*15,000*			
		4	*15,000*			
3	Tridem	*3*	*16,000*	*48,000*	*39,000*	*9,000*
		3	*16,000*			
		3	*16,000*			
4	Quint	*5*	*16,200*	*81,000*	*74,000*	*7,000*
		5	*16,200*			
		5	*16,200*			
		5	*16,200*			
		5	*16,200*			
5	Tandem	*2*	*23,000*	*46,000*	*35,100*	*10,900*
		2	*23,000*			

Table 26. Loading configuration for Case 10.

Group	Axle Type	Axle code	Axle weight (lbs.)	Axle-Group weight (lbs.)	Axle-Group weight limit (lbs.)	Excess axle-group weight (lbs.)
1	Steer	*1*	*21,450*	*20,000*	*21,600*	----
2	Quad	*4*	*20,625*	*82,500*	*42,900*	*39,600*
		4	*20,625*			
		4	*20,625*			
		4	*20,625*			
3	Tridem	*3*	*22,000*	*66,000*	*39,000*	*27,000*
		3	*22,000*			
		3	*22,000*			
4	Tridem	*3*	*21,000*	*65,000*	*39,000*	*26,000*
		3	*21,000*			
		3	*23,000*			
5	Tridem	*3*	*23,000*	*69,000*	*39,000*	*30,000*
		3	*23,000*			
		3	*23,000*			

3.3.2 Fixed vehicle analysis results

The results of the fixed vehicle damage analysis conducted on the 10 cases using the AASHTO equations are presented in Figure 34. Combining the individual axle-group EALFs into a single ESAL for the overweight vehicle allows for comparative damage analysis. Figure 34 shows that the axle configuration and axle loading in case 3 causes the most damage to the pavement structure. Even though the GVW in case 3 (225 kips) is below that of cases 2 (246 kips), 8 (324 kips), 9 (255 kips), and 10 (304 kips). Note also that the legal load (not charged an overweight fee) also carries an inherent 'allowed damage'. Overweight vehicles should be assessed overweight fees based on the damage caused in excess of that caused by the legal weights. Thus, the ESALs are better presented in terms of the normalized ESAL, i.e., the relative damage compared to the legal load damage, or the excess ESAL, i.e., the net additional damage caused by the overweight vehicle. Normalized and excess ESAL values for the 10 cases are presented in Figures 35 and 36, respectively.

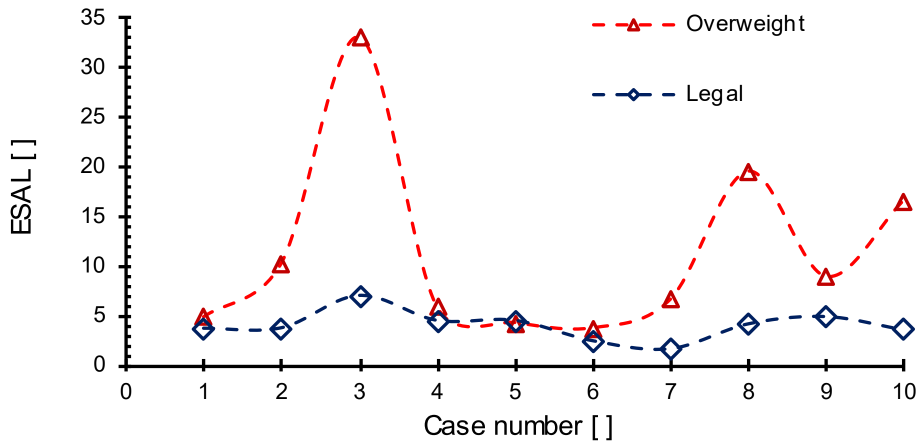

Figure 34. Fixed vehicle damage analysis results in equivalent 18-kip single axle loads (ESAL) for the 10 representative overweight vehicle loads identified as part of Task 1. Overweight ESALs are compared to the legal ESALs in each case.

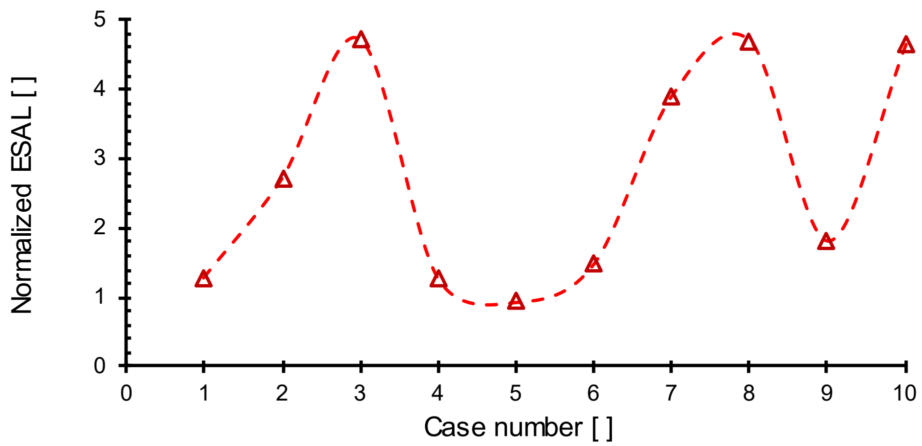

Figure 35. Overweight vehicle ESALs normalized by the legal weight ESALs. The data shows the relative damage caused by the overweight vehicle.

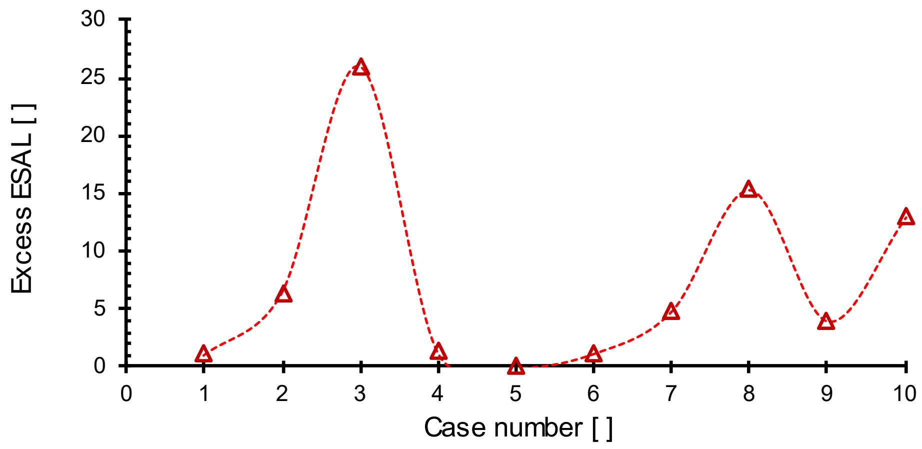

Figure 36. Number of ESALs by which the overweight vehicle exceeds the ESALs associated with the legal axle load limits.

The normalized ESALs show that the relative damages caused by cases 3, 8 and 10 is about 5 times the damage caused by their corresponding legal loads. However, since the legal load limits cause different amounts of damage (see blue line in Figure 34), their net damage is substantially different (see Figure 36). In fact, the excess ESAL data is more advantageous because it facilitates a direct comparison with the legal loading and across the different cases. Figure 37 shows a juxtaposition of the excess ESAL for all cases against the current overweight vehicle fees charged by the state of New Mexico. Figure 38 shows a similar comparison against the average fees charged by Arizona, Colorado, Oklahoma, and Texas. Fees for the five states are presented for each case in Table 27.

Table 27. Permit fees by case for each state. NM charges the lowest fees of all five states in all but one case.

PERMIT INFORMATION			PERMIT FEE					
Case	**GVW [lbs]**	**Route [mi]**	**AZ**	**CO**	**OK**	**TX**	**Avg.**	**NM**
1	100,000	98	$ 75.00	$ 90.00	$ 240.00	$ 210.00	$ 131.33	$ 41.66
2	246,000	76	$ 280.00	$ 250.00	$ 1,800.00	$ 1,405.00	$ 782.32	$ 176.62
3	226,500	192	$ 570.00	-	$ 1,700.00	$ 1,405.00	$ 1,009.06	$ 361.24
4	90000	396	$ 75.00	$ 80.00	$ 200.00	$ 210.00	$ 121.56	$ 42.82
5	80000	371	$ 15.00	$ 30.00	$ 43.68	$ 60.00	$ 34.74	$ 25.00
6	72000	78	$ 75.00	$ 70.00	$ 43.68	$ 31.00	$ 48.94	$ 25.00
7	110000	42	$ 75.00	$ 80.00	$ 43.68	-	$ 59.02	$ 37.39
8	324100	123	$ 397.50	-	$ 2,521.00	$ 1,405.00	$ 1,178.49	$ 390.46
9	255000	123	$ 397.50	-	$ 1,830.00	$ 1,405.00	$ 979.18	$ 284.22
10	303950	123	$ 397.50	-	$ 2,319.50	$ 1,405.00	$ 1,120.37	$ 359.48

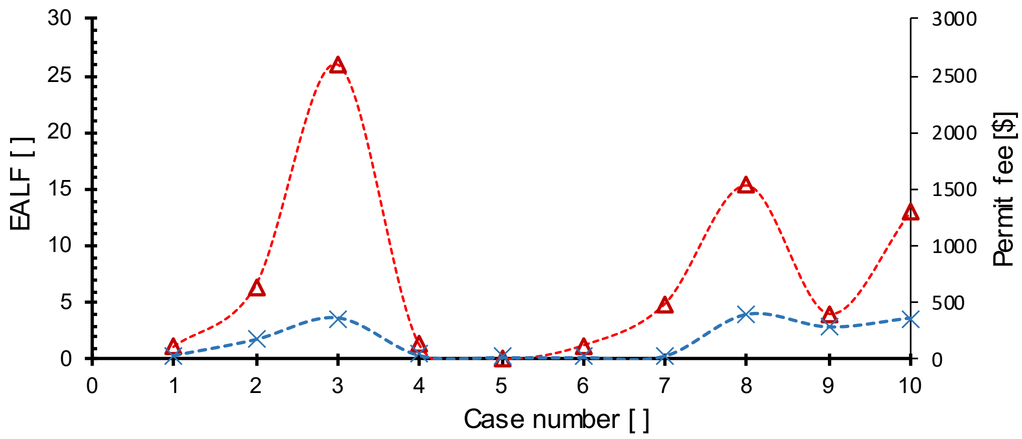

Figure 37. Comparison of excess ESAL and current permit fees charged by New Mexico.

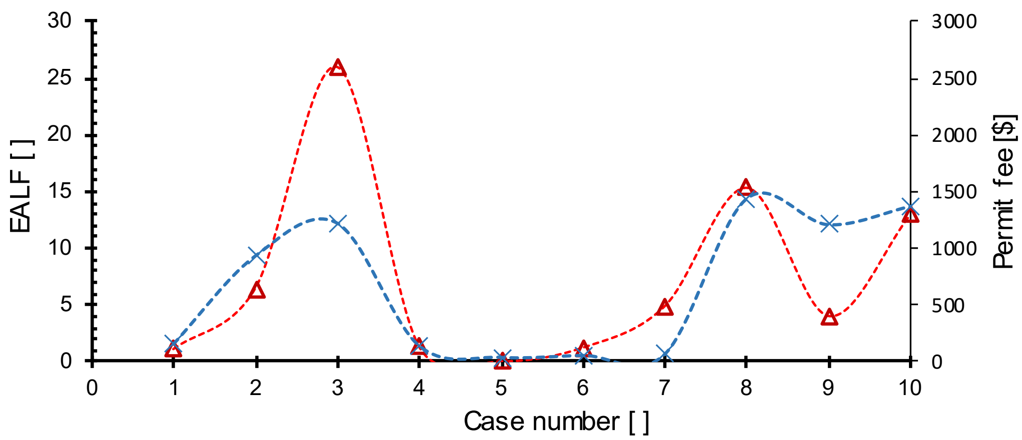

Figure 38. Comparison of excess ESAL and average permit fees charged by four neighboring states.

Despite the differences in the magnitude of the fees charged by the five states, the fees appear to more closely follow the effect of gross vehicle weight as opposed to cumulative axle damage. Cases 2, 3, 8, 9, and 10 are charged similar fees even though there is a substantial difference in the pavement damage caused by each. In all cases, states fail to assess a higher fee to the vehicle that causes the most pavement damage (Case 3) while charging more to other vehicles (cases 2 and 9) based on their relative damage.

4. TASK 3 (BRIDGES)

OW TRANSPORTATION INFRASTRUCTURE DAMAGE ANALYSIS

4.1. Introduction

Successful bridge management programs require robust methods to assess bridge condition. The Federal Highway Administration (FHWA) has invested several billion dollars in federal funding to address the aging and deterioration of the U.S. transportation network including highways and bridges [53]. This effort has been ongoing over the past 20 years. It is essential that transportation agencies prioritize their distribution of limited funding resources to maintain a state of good repair of bridges in their inventory [53]. Although maintenance is meant to keep existing bridges in serviceable and safe conditions, the replacement of deficient bridges may be necessary when maintenance efforts are not adequate. It is estimated that an annual investment of $20.5 billion is required to replace deficient bridges in the U.S. by 2028 [51].

The number of oversize and overweight (OS/OW) vehicles on roads and bridges has increased because of the continuous increase in the amount of U.S. freight tonnage [44]. The applied loads of OS/OW trucks accelerates the deterioration process and compromises the safety of bridges [51]. Consequently, transportation agencies need to have procedures in place to evaluate the adverse effects of OS/OW vehicles on the transportation network [77].

Several U.S. states have conducted studies to evaluate the factors that influence the deterioration rate and the costs associated with OW trucks on their bridge network. Table 28 lists the U. S. studies conducted within the last 20 years related to the impacts of OW vehicles on transportation networks.

Table 28. List of U.S. studies related to OW trucks.

Authors	Year	State	WIM Data	Permit Data	NBI Data[2]	LCCA[1]
Roberts et al.	2005	LA	NO	YES	Low	YES
Straus and Semmens	2006	AZ	YES	NO	Low	YES
Prozzi et al.	2012	TX	YES	YES	Medium	YES
Lin et al.	2012	WI	NO	YES	Low	NO
Chowdhury et al.	2013	SC	YES	YES	Medium	NO
Ghosn et al.	2015	NY	YES	YES	Medium	YES
Al-Qadi et al.	2017	IL	YES	YES	High	YES

[1] Life-cycle cost analysis (LCCA) is a method for assessing the total cost of transportation infrastructure ownership. It considers all costs of acquiring, owning, and disposing of a building or building system.

[2]Number of NBI data items used: high (> 20), medium (4 to 20), low (< 4)

The number of OS/OW vehicle permits in the U.S. has grown rapidly during recent years. Life-cycle cost analysis (LCCA) was applied by several U.S. states to address the cost of deterioration caused by the increased volume of OS/OW vehicles. In general, the remaining service life of a bridge is estimated and translated to life consumption (e.g., reduction in service life of bridge decks) imposed by OW vehicles. Then, based on the calculated life reduction, a cost analysis is performed to quantify the dollar amount of deterioration.

Figure 39 shows a simplified flowchart of the general approach applied in a few U.S. states to estimate the costs of damage caused by OW vehicles based on a data-driven process. The following section summarizes the studies listed in Table 28 conducted by the state Departments of Transportation (DOTs) to develop a new permit fee structure in Arizona [76], Texas [73], South Carolina [47], New York [56], and Illinois [34].

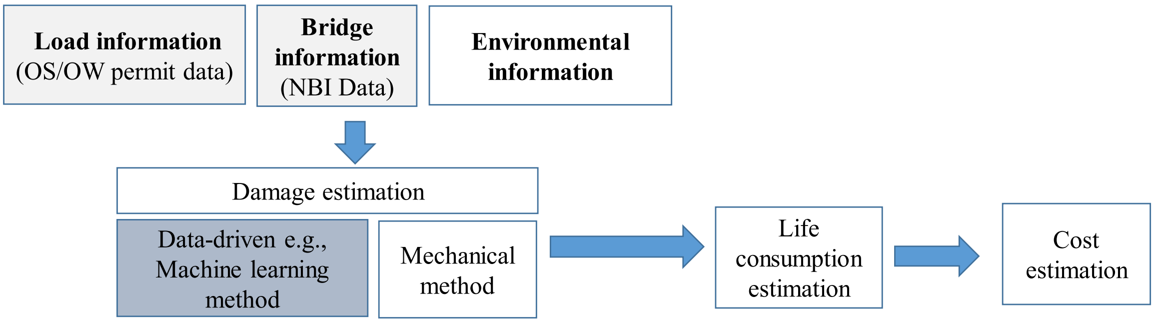

Figure 39. Flowchart cost estimation associated with OW vehicles.

4.2. State DOT studies

Arizona:
In the state of Arizona, Straus and Semmens [76] provided an estimate of highway damage costs (including bridges and pavement) caused by OW vehicles based on truck load information collected from manual and automated traffic counting techniques as well as weigh-in-motion (WIM) sensors. The Arizona DOT used several types of technology for automated traffic counting; automatic traffic recorders (usually inductive loop detectors) are primarily used at continuous monitoring sites and pneumatic tube detectors for short-term counts. Tubes or loops are generally used to obtain raw traffic counts that are subsequently processed and converted to average annual daily traffic volumes (AADTs).

In the Arizona study, the federal bridge formula is used to determine the axle weights for overweight vehicles as follows:

$$W = [LN/N\text{-}1 + 12N + 36] \qquad \text{Eq. 87}$$

where W represents the maximum weight in pounds that can be carried by a group of two or more axles to the nearest 500 pounds, L denotes the distance between the outer axles of the group and N represents the number of axles in the considered group.

ADOT did not determine damage of OW vehicles to bridges and pavements; instead they perfumed a revenue analysis to roughly estimate the cost of damage caused by OW vehicles. Based on a Highway Cost Allocation Model employed by ADOT's Financial Management Services Section, the authors estimated the irrecoverable damage attributed to OW vehicles on Arizona's transportation system to be between \$12 million and \$53 million (per annum). The damage costs were determined from reliability analysis based on the premise that "the relative damaging effect of an axle is considered to be approximately proportional to the fourth power of the load" [76]. Using 4.5% and 12% thresholds (equivalent to excess weights of 3,000 and 8,000 lbs. for two tandem axles) and fourth-power exponentials, the cost of damage originally estimated was adjusted to be between \$10 million to \$35 million. In other words, it was estimated that the overweight vehicles would exert 19% ($1.045^4 = 1.19$) and 57% ($1.12^4 = 1.57$) more damage than a truck operating at the 80,000 lb. legal limit based on the two thresholds.

The authors concluded that the expansion of mobile enforcement would yield a benefit/cost ratio of approximately 4:1 to 5:1. That is, infrastructure damage equivalent to a cost of \$4.50 would be prevented for each dollar invested in motor carrier enforcement [76]. In this study, the authors didn't propose any new permit fee structures.

Texas:
Prozzi et al. [73] used mechanical-based methods to calculate the consumption rates per mile of bridges and pavements. The fees per mile were calculated for all OW vehicle axle configurations and all highway and non-routed bridges and pavements. For the bridge consumption analyses, information stored in the Texas DOT Bridge Inspection and Appraisal Program (BRINSAP) database was used. Vehicle load and configuration from permit data and the designated routes were used to calculate accelerated bridge consumption rates per Vehicle Miles Traveled (VMT) for the state OS/OW vehicles. The rate/VMT varies depending on the route traveled and the quantity and types of bridges crossed. This was done to provide a bridge consumption rate/VMT compatible with the rate/VMT for pavements.

The authors used the Texas DOT BRINSAP database, the Central Permit Office database, and 2009 GIS routed permit data [68]. Non-routed information (including annual mileage and most common load configurations) from the Rider 36 project [73] were also used. The OS/OW permit data was first filtered to identify the most common OW vehicles (similar to the approach taken in Task 1 of this study). For selected bridges, relevant NBI data features such as span length, bridge configuration, and material type were extracted to compute the magnitudes of bending moments under the loading from the OW vehicles and to estimate the remaining service life based on the AASHTO fatigue charts. The cost-per-bridge on each GIS segment and finally, the cost-per-mile for each permit GVW weight category was computed using the following formula:

$$Consumption_{OSOW} = [(Area)(190)(0.11)\left(\frac{M_{OSOW}}{M_{Inventory}}\right)^{m}] \div 2{,}000{,}000 \qquad \text{Eq. 98}$$

where $M_{Inventory}$ where M_{OSOW} denote the live-load bending moments for the inventory rating load and OW vehicle load for each bridge in the permit dataset, m is a material dependent constant, 190 is a bridge asset value in dollars per square foot of deck, 0.11 is the bridge asset value responsibility for heavy trucks, and 2,000,000 is the number of load cycles that define bridge design life according to AASHTO.

The authors conducted a revenue analysis based on the new permit fee structure for comparison with the existing permit numbers and associated revenue. The authors estimated the revenue to be $521.4 million based on the new permit fee structure that considers both pavement and bridge consumption. The revenue for vehicles that are currently exempt from paying permit fees was estimated to be approximately $150 million (approximately 30% of total) using the new permit fee structure.

South Carolina:
Chowdhury et al. [39] investigated the impact of heavy vehicle traffic on pavements and bridges in South Carolina using WIM sensors and permit data. The authors performed finite element (FE) analyses to assess bridge damage. A series of truck models were first developed representing the most common OW vehicles in South Carolina. The authors also developed groups of bridges that share common features and structural characteristics in South Carolina ("Archetype" bridges). Bridge information such as the material type, span length, quantity, location, etc. were obtained from the National Bridge Inventory (NBI) database. Using the LS-DYNA program, the stress ranges for the "Archetype" bridges under OW vehicles were determined along with the associated bridge fatigue lives (similar to Texas). The total bridge fatigue damage (D) is taken as the sum of fatigue damage from all truck models as follows:

$$Fatigue\ Damage\ (D) = \frac{N_{Ci,1}}{N_{i,1}} + \frac{N_{Ci,2}}{N_{i,2}} + \frac{N_{Ci,3}}{N_{i,3}}$$ Eq. 109

where $N_{Ci,1}$, $N_{Ci,2}$, and $N_{Ci,3}$ equal the number of load cycles consumed by the i-th truck model with gross vehicle weight levels 1 to 3 (GVW1, GVW2, GVW3), respectively; $N_{C,1}$, $N_{C,2}$, and $N_{C,3}$ are the corresponding allowable number of load cycles.

The D-value is a unitless quantity ranging from zero (no damage) to one (complete damage under repetitive fatigue loading). Based on the D-value results, the authors found that the bridge damage increased exponentially with an increase in truck weight and proposed a flat fee of $65 per trip to recover South Carolina's highway damages. Permit fees for the different truck models costing from $24 to $175 per trip based on load, vehicle configuration, and trip distance were also proposed [39].

New York:

Ghosn et al. [56] developed a methodology to estimate damage caused by different categories of OW trucks on pavements and bridges in New York State. The authors used a data-driven model based on WIM sensor data and permit data. A statistical approach was proposed using a Bayesian model to simulate bridge deterioration. The authors analyzed the New York State DOT permit load databases for divisible (DV) and special hauling (SH) trucks to build pattern recognition rules that cluster the OW permits into groups based on axle spacings, FHWA classes, and truck lengths. Note that a "divisible load" is any vehicle or combination of vehicles transporting a cargo of legal dimensions that can be divided into units of legal weight without affecting the physical integrity of the load. For each cluster, the characteristics were defined consisting of the upper and lower bounds for the axle spacings, and the upper bounds of the allowed GVWs and axle weights. The WIM systems were used to assemble a truck database representative of the vehicles that travel on a given highway.

In the "structural analysis" phase, OS/OW vehicle data were extracted from the WIM database and pertinent bridge data were extracted from the National Bridge Inventory (NBI) and WINBOLTS databases to determine the maximum bending moments for each bridge selected for analysis. The WINBOLTS database is the bridge database put together by the NYSDOT for all bridges under the New York jurisdiction. In the "damage analysis" phase, the overstress and fatigue effects for each truck on the primary longitudinal member for each bridge were calculated. Ultimately, the load effects produced by each overweight truck in the WIM database were used to estimate the costs imposed by each OW truck on each bridge. The procedure to determine the overstress effect was based on FHWA cost allocation methodology.

The authors estimated that trucks carrying divisible loads may be responsible for $50M per year in New York State bridge infrastructure cost associated with maintenance, rehabilitation, and replacement. Trucks with special hauling permits may be responsible for $2M per year in additional cost, and illegally overweight trucks may be responsible for $43M per year for a total of $95M per year [56].

Illinois:

In the state of Illinois [42], the effects of OW vehicles were evaluated with respect to three facets of the transportation system (pavements, bridges, and traffic safety). The authors proposed fees and carried out an independent cost analysis for each facet using a data-driven approach. Support vector machine (SVM) and regression prediction/classification algorithms were applied to model bridge degradation by inputting traffic database and WIM sensor data.

The authors used NBI data to define the bridge characteristics. The calculated Vehicle Weight Frequency (VWF) from WIM stations for each bridge and the pertinent variables from the NBI data were provided as prediction engine inputs and the bridge deck condition was the output. Subsequently, the expected service life of bridges was estimated based on two scenarios: with and without damaging loads (defined as the difference between the applied load and inventory rating load). Service life is correlated to bridge life-cycle consumption to assess the cost of the damaging loads and then converted to the permit fee.

The following equation was used to determine the average per mile cost of bridge damage:

$$Average\ per\ mile\ cost\ of\ damage = \left(\frac{\$3.93E-6}{\Delta kip-ft^2}\right) * (10{,}679\ ft^2) * (6919\ bridges) * \left(\frac{1}{15{,}969\ miles}\right) = \frac{\$0.0182}{mi*\Delta kip} \qquad \text{Eq. 22}$$

where *6919* is the modified number of bridges, *15,969* is the centerline mileage, and *10,679* ft^2 is the average deck area reported by IDOT for state-owned bridges. The *3.93E-6*/$\Delta kip*ft^2$ factor is the average cost of permit fees related to bridge damage and Δkip is calculated by subtracting the gross weight of an OW vehicle from the average inventory rating of state-owned bridges from the NBI; i.e., $\Delta kip = OW_{gross} - AVG\ Inventory\ Rating_{gross}$ (2015 NBI data = 80.38 kips).

Why data-driven approach? In general, a data-driven approach provides the capability to predict bridge condition that can then be used as a quantitative feature for evaluating the damage caused by OW vehicles. Several researchers have studied damage cost estimation using deterioration prediction models. Such prediction models were utilized to calculate the impacts of OS/OW vehicles on pavements and bridges. These models could be categorized into three different groups. Deterministic models use independent variables like age, average daily traffic, material properties, etc. to model the bridge component deterioration. These variables are normally selected by engineering judgment with trial and error which is a time-consuming task [57][66][69]. Probabilistic models consider the deterioration process as a stochastic process and account for inherent uncertainty and nonlinearity due to the existence of measurement errors such as unobserved variables [67]. One of the most common probabilistic approaches for deterioration process modeling is the Markovian method [55][70][74]. Although they have been successful in modeling the deterioration process with acceptable accuracy, drawbacks of these methods are a high computational cost and complex computation for large models [66].

Data-driven methods based on machine learning assess deterioration through the capture of data abstraction from training datasets [60][62][64]. Machine learning methods can identify patterns, can continuously self-update for better accuracy, and facilitate the processing and interpretation of multi-dimensional data. In summary, in a data-driven approach, the prediction results using a machine learning model are used as parameters to estimate life consumption. Figure 40 shows the four aspects of a data-driven prediction model. The objective of the model is to correlate the applied OW vehicle load (load intensity and frequency) and bridge data (e.g., age and materials) with general bridge condition ratings.

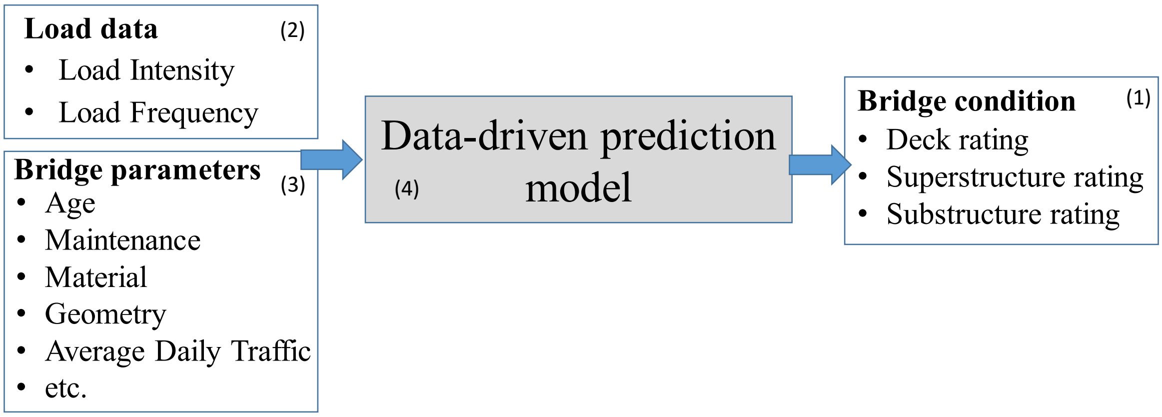

Figure 40. Flowchart to predict bridge condition based on permit and NBI data.

4.3. Data preparation and processing

In a data-driven approach, evaluating the impact of OS/OW vehicles requires knowledge of the current and future condition states of bridges in the state inventory. In this study, a decrease in the condition rating of a bridge is taken to signify the extent of which deterioration or damage has advanced. Thus, it was first necessary to identify the key features needed to effectively forecast bridge conditions from the following two databases:

1. National Bridge Inventory (NBI) data
2. OS/OW Permit data

4.3.1 National Bridge Inventory (NBI) dataset

The FHWA manages the NBI database which contains information related to the design, materials, condition ratings, traffic, and structure type of over 675,000 bridges. The database is maintained and updated frequently, and includes 138 features for each bridge which are categorized as follows [52]:

- Identification data (e.g., bridge ID, location, longitude, and latitude)
- Service data (e.g., number of lanes, year constructed, and average daily traffic (ADT))
- Navigation data (e.g., navigational service, and pier and deck protection)
- Condition data (e.g., superstructure, substructure, and deck condition ratings)
- Posting and load rating data
- Inspection data (e.g., maintenance date, routine inspection, and intervals)
- Structure and material data (e.g., material types and structure types of all components such as deck protection and wearing surface)
- Geometric data (e.g., width and span length)

Statistical methods have previously been used to identify features that affect bridge conditions [42][53]. General condition ratings (GCRs) are assigned to the three bridge components (deck, superstructure, and substructure), and range from a value of zero (worst condition) to nine (best condition). In this study, the NBI data was filtered and cleaned as follows:

- Rows with a blank cell are removed.
- Non-applicable records or entries (i.e., missing values) are removed from the features.
- Duplicate entries, observations, or rows are removed. There are certain rows in the NBI data with the same date for the year of construction and reconstruction year. These records are omitted from the NBI dataset.

The NBI dataset provides the bridge locations (latitudes and longitudes) in degree, minute, and second (DMS) format which was converted to decimal degree (DD) format using the following equation:

$$DD = D + \left(\frac{M}{60}\right) + \left(\frac{S}{3600}\right) \qquad \text{Eq. 25}$$

The bridges in New Mexico are mapped in Figures 41-43 according to their 2019 NBI condition ratings (the most current at the time of this study) for the deck, substructure, and superstructure.

From Figures 41 through 43, the bridges with the highest deterioration rates (which could be caused in large part by OW loads) are not apparent. To determine these "critical zones" of bridges, the differential condition rating (equal to the change in the condition rating values between two consecutive inspections) is a better measure than solely the condition ratings for a particular inspection year. Bridges are typically inspected every two years. Figures 44 through 46 show the difference in condition ratings between 2017 and 2019 for the deck, substructure, and superstructure components; positive values signify the condition improved and negative values the condition worsened.

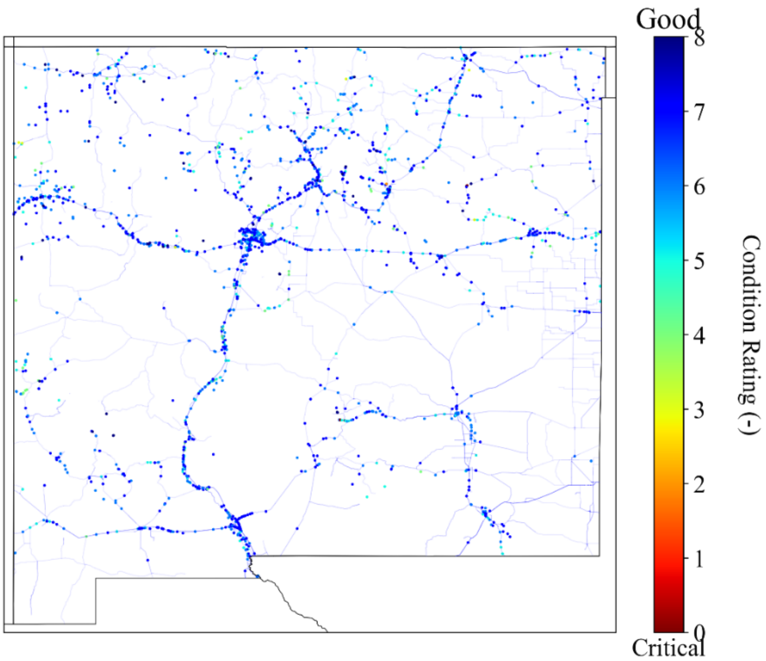

Figure 41. Deck condition of New Mexico's bridges.

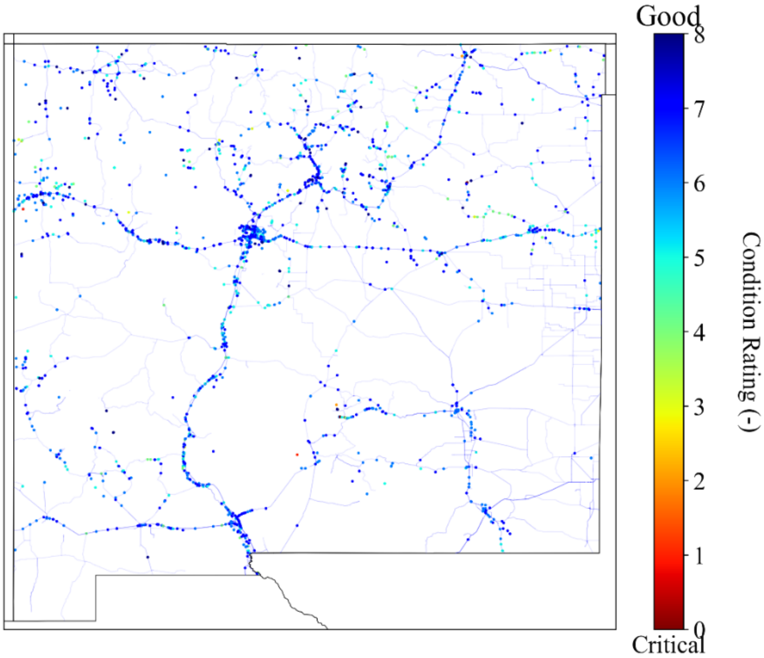

Figure 42. Substructure condition of New Mexico’s bridges.

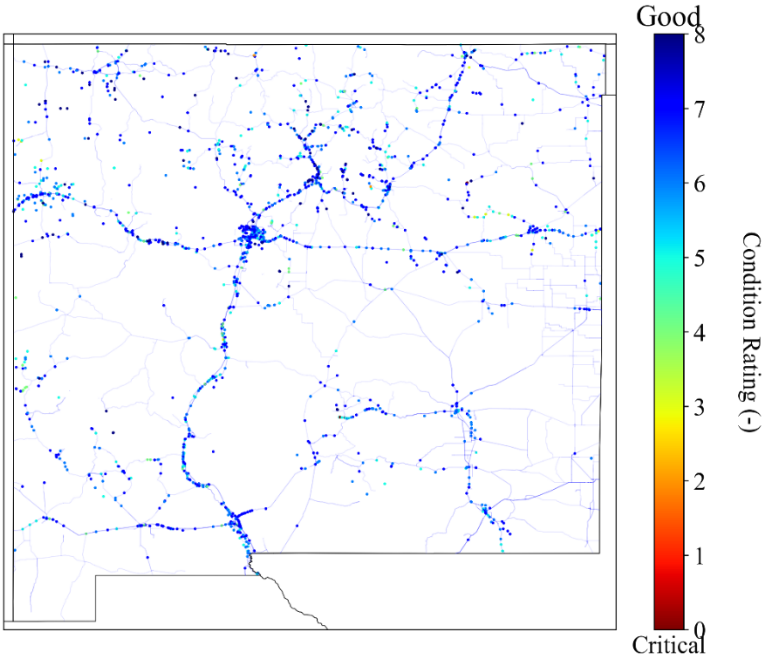

Figure 43. Superstructure condition of New Mexico’s bridges.

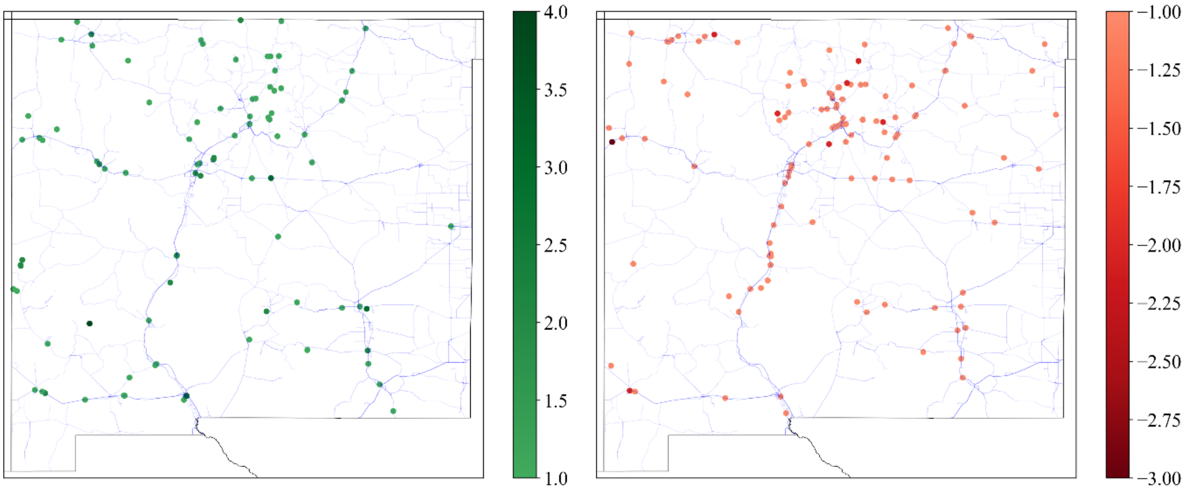

Figure 44. Change in deck condition ratings (2017-2019): left – improved, right – degraded.

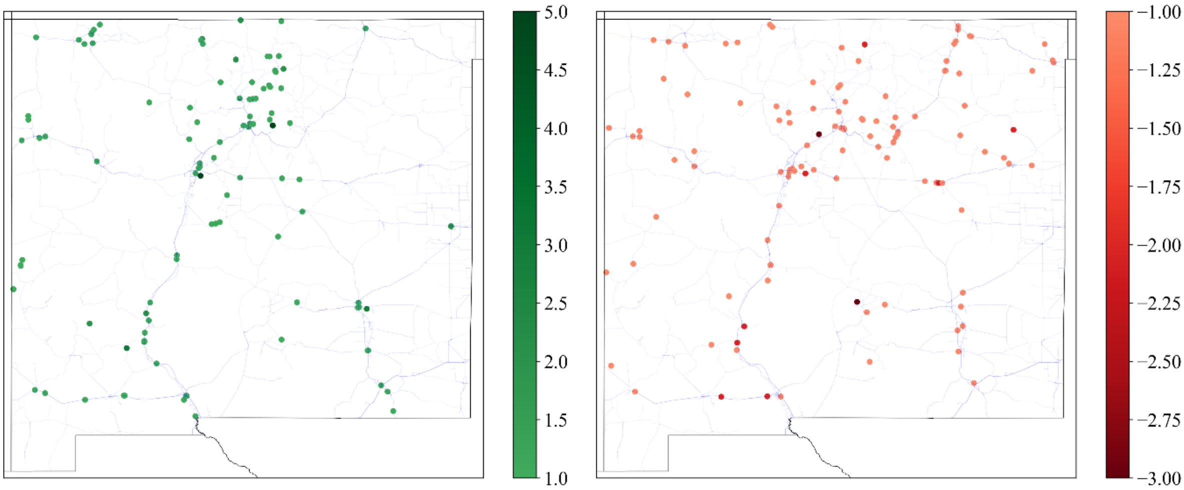

Figure 45. Change in substructure condition ratings (2017-2019): left – improved, right – degraded.

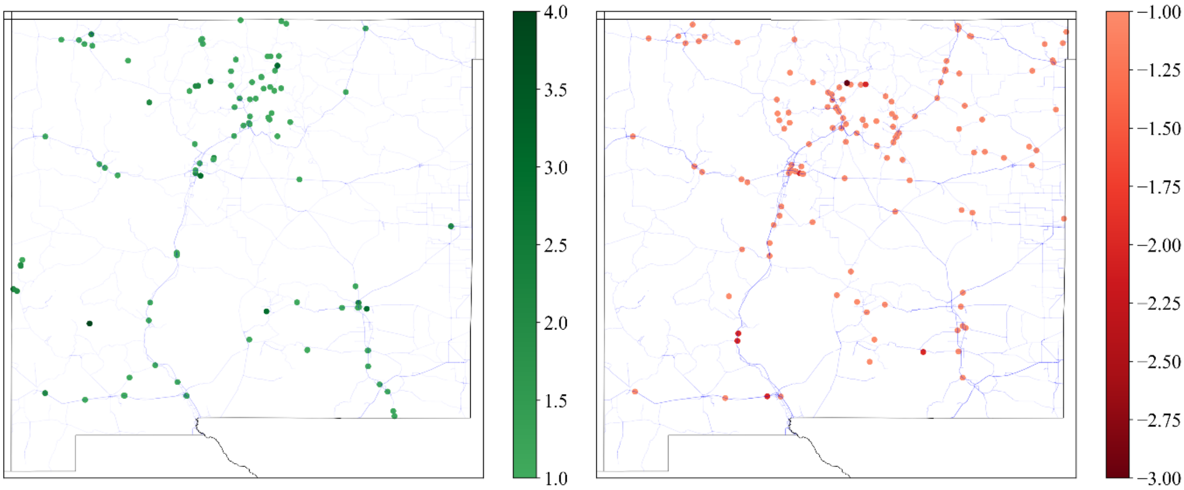

Figure 46. Change in superstructure condition ratings (2017-2019): left – improved, right – degraded.

The rating differences provide valuable information on the bridge condition changes. To better visualize the changes, a smoothing process was applied by the research team based on the Gaussian distribution to develop a contour map for bridges with decreasing ratings from 2017 to 2019. Figure 47 shows the critical zones in New Mexico where the bridge deck conditions decreased the most from 2017 to 2019.

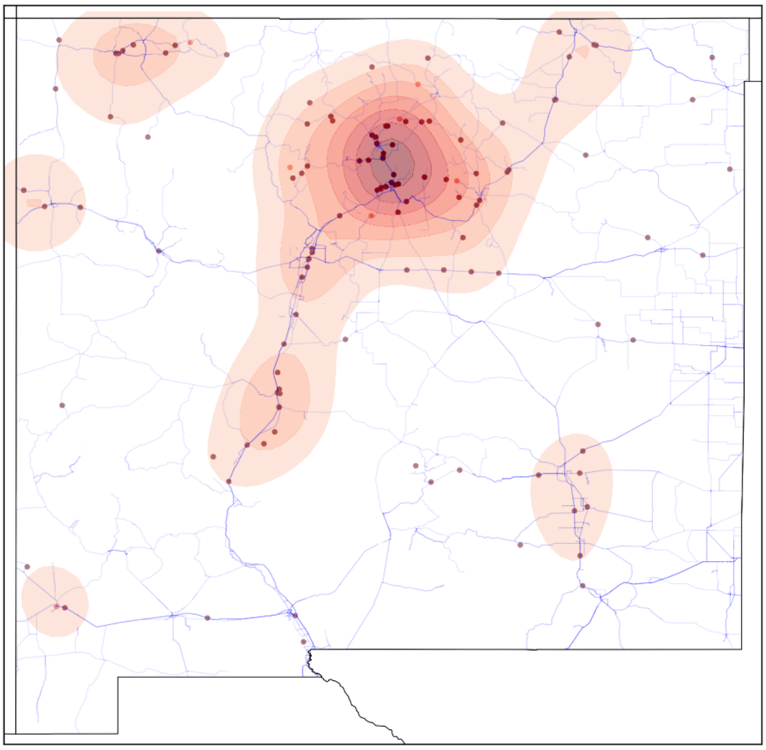

Figure 47. Critical bridge zones in New Mexico based on deck condition.

Figure 47 highlights the critical zones of bridge groups with the highest deck deterioration rates between 2017 and 2019. The zones were generated using multivariate normal distribution as follows:

$$f(x) = A \frac{\exp(-\frac{1}{2}(x-\mu)^T \Sigma^{-1}(x-\mu))}{\sqrt{(2\pi)^k |\Sigma|}} \qquad \text{Eq. 26}$$

where x is a 2-dimensional column vector and $|\Sigma| \equiv \det \Sigma$ is the generalized variance. The covariance was selected as 0.09 miles. The mean value is denoted by μ which is the location of each degraded bridge and the amplification factor A is the change in condition rating between two consecutive inspection years. Superimposing the Gaussian functions in the single map shown in Figure 44 delineates the critical zones. Bridges located in zones with darker contours represent those with deterioration or damage that has advanced most. In addition, the different contours provide useful information for state decision-makers to identify regions in the State where maintenance and/or repair is most needed and to allocate resources for such purposes.

This section provided insight into the change in bridge conditions across New Mexico from 2017 to 2019. Bridge deterioration can be related to different factors (e.g., age, OW loads, the volume of traffic, environmental conditions, etc.) that must be investigated. The following section analyzes the intensity (i.e., load magnitude) and frequency of the OS/OW vehicles crossing New Mexico's bridges with respect to the changes in the condition ratings.

4.3.2 Permit data

Promiles company, which issues OS/OW vehicle permits for the New Mexico Department of Transportation (NMDOT), provided four years of permit data for vehicles registered in their online permit fee system. The Promiles dataset contains the following features: permit type, company name, load description, permit cost, start date, end date, vehicle type, loaded length, loaded height, GVW, axle weights, axle spacings, axle widths, traveled route, and total trip miles. Monthly shapefiles were provided to correlate the permit data with the latitudes and longitudes of the trip origin and destination. It should be noted that the data on axle weights and spacings are limited to the first 15 axles; a few permits had over 15 axles.

Based on the AASHTO fatigue chart, load frequency and intensity are two important factors affecting bridge deterioration [71]. The Promiles permit data was used to calculate the load frequency for each OS/OW permit type which we define as the average daily permit traffic (ADPT). The average GVWs of the OS/OW trucks crossing each bridge was used to define the load intensity. It should be noted that the average daily traffic (ADT) reported in the NBI dataset does not distinguish OS/OW traffic from other vehicles and the ADPT used in this study focuses solely on the five OS/OW permit types of concern in New Mexico [50]. The ADPT and average GVW for each bridge was calculated as follows:

- Annual number of vehicles in each permit category traveling on primary and secondary routes in New Mexico is calculated and divided by 365 to determine the ADPT.
- Annual cumulative GVW of vehicles in each permit category is determined and divided by the number of vehicles to determine the average annual GVW.

In Task 1, five OS/OW permit types were identified based on load frequency or intensity (OS, OW, OS/OW, superload, and self-propelled). The ADPT value for these permit types in comparison with all permit types for 2019 for each bridge are displayed in Figures 48 through 53; statistical information for the ADPT values are given in Table 29.

Table 29. ADPT statistics breakdown.

	Maximum ADPT	Average ADPT	Standard Deviation
All Permits	100.55	2.51	8.99
OS Permit	15.84	0.70	2.31
OW Permit	0.89	0.04	0.13
OS/OW Permit	8.25	0.39	1.18
Superload Permit	0.38	0.01	0.04
Self-Propelled Permit	0.53	0.02	0.07

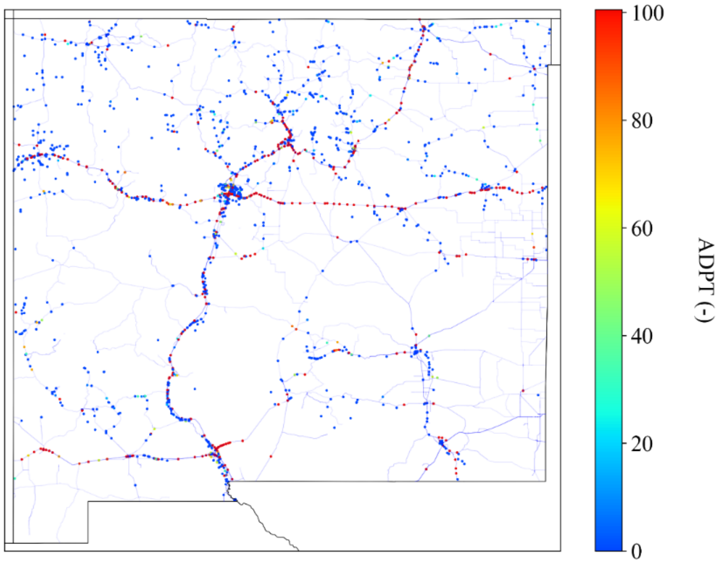

Figure 48. ADPT of all vehicles on NM bridges in 2019.

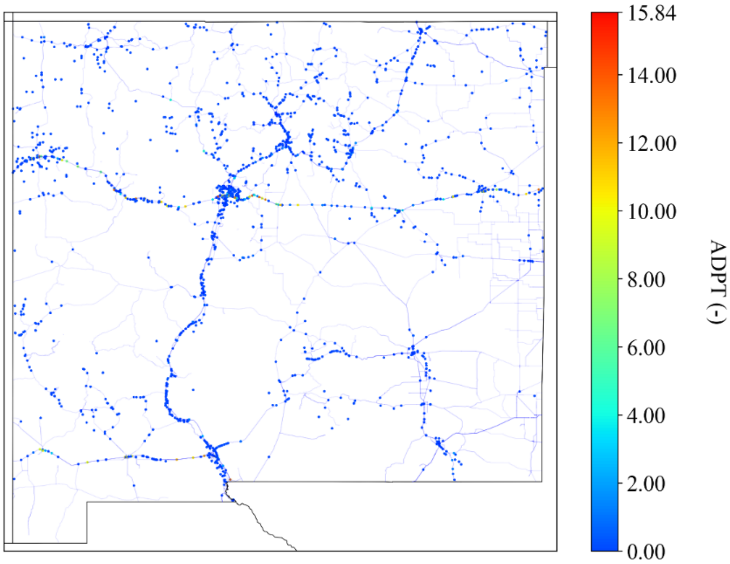

Figure 49. ADPT of OS vehicles on NM bridges in 2019.

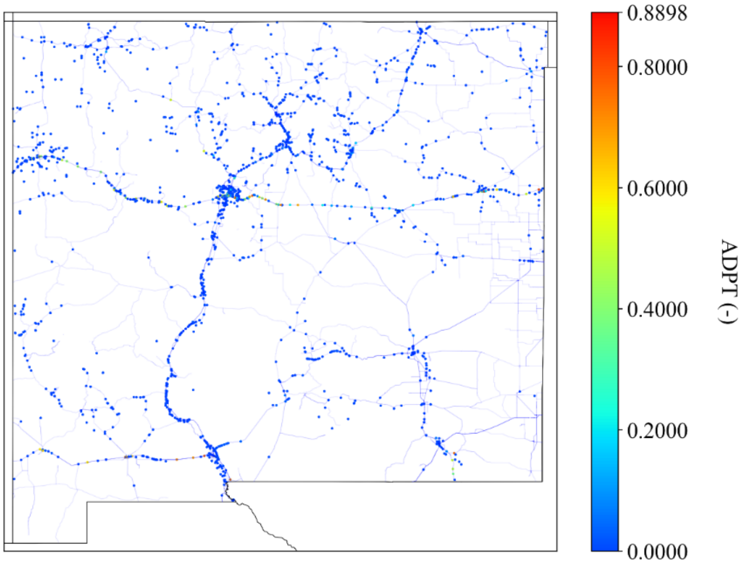

Figure 50. ADPT of OW vehicles on NM bridges in 2019.

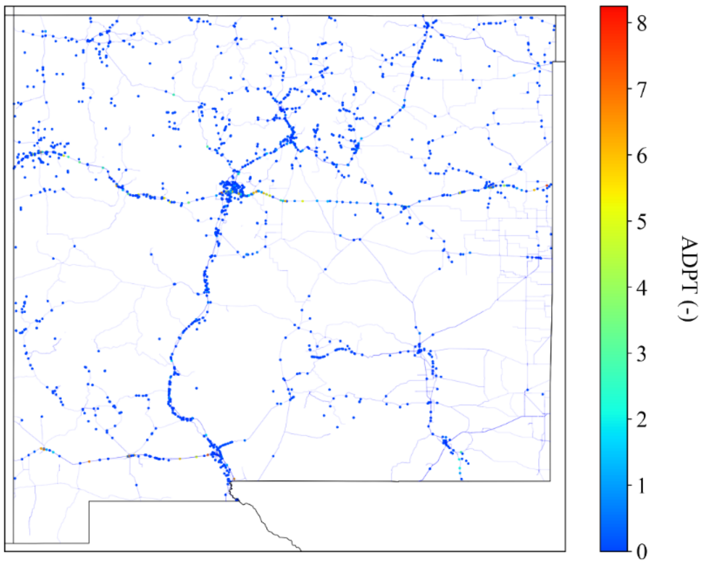

Figure 51. ADPT of OS/OW vehicles on NM bridges in 2019.

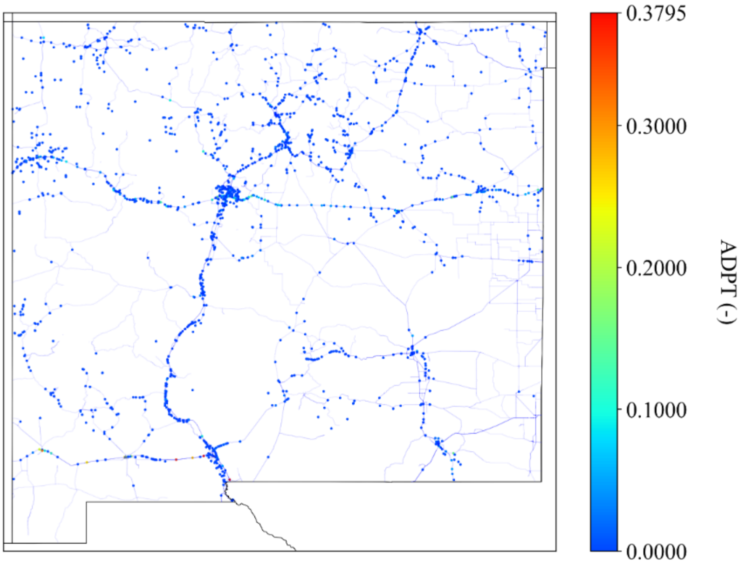

Figure 52. ADPT of superload vehicles on NM bridges in 2019.

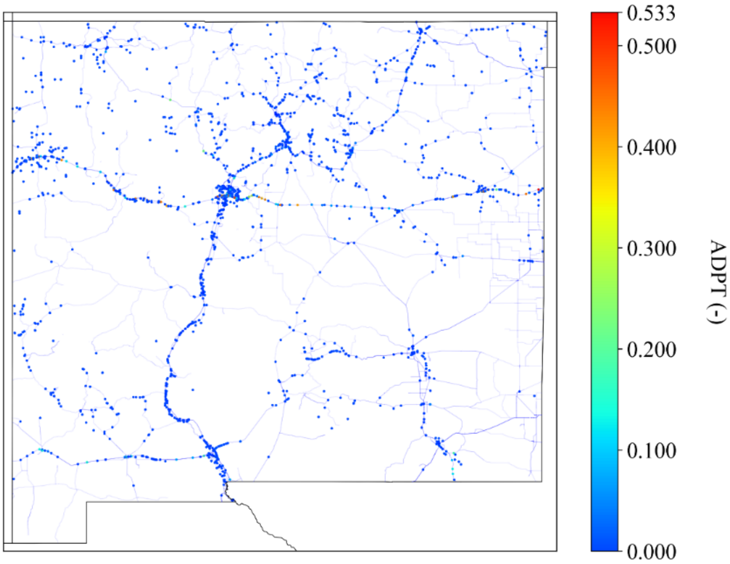

Figure 53. ADPT of self-propelled vehicles on NM bridges in 2019.

Of the five permit categories, the OS category had the maximum vehicle traffic volume in 2019 and the superload category had the least frequency. In addition, bridges located on interstate highways I-40 and I-25 experience the maximum permit load frequency. The statistical values of the 2019 GVW data for permitted vehicles in New Mexico are reported in Table 30 and Figures 54 through 59. In summary, Figures 48 through 53 identify the most frequent routes used by vehicles in each permit category whereas Figures 54 through 59 identify the intensity of the loads applied on bridges across New Mexico.

Table 30. Statistics breakdown for annual cumulative GVWs for NM bridges.

	Maximum GVW (lbs.)	Average GVW (lbs.)	Standard Deviation (lbs.)
All Permits	93521.72	47214.60	31565.47
OS Permit	80000.00	74465.80	8832.11
OW Permit	132044.00	96976.09	6925.28
OS/OW Permit	193221.31	113416.58	14839.68
Superload Permit	747092.00	236326.07	41887.40
Self-Propelled Permit	199393.0	90017.03	25326.75

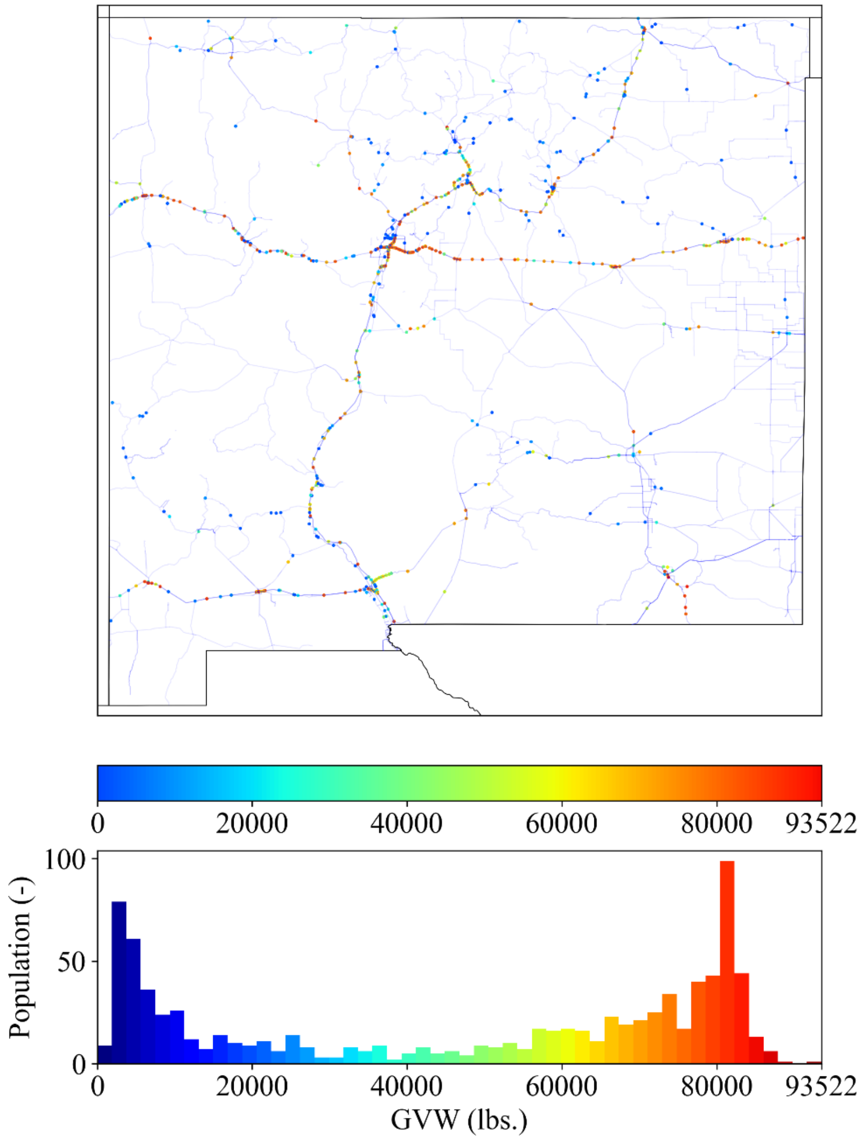

Figure 54. Average GVW for all permitted vehicles (lbs.)

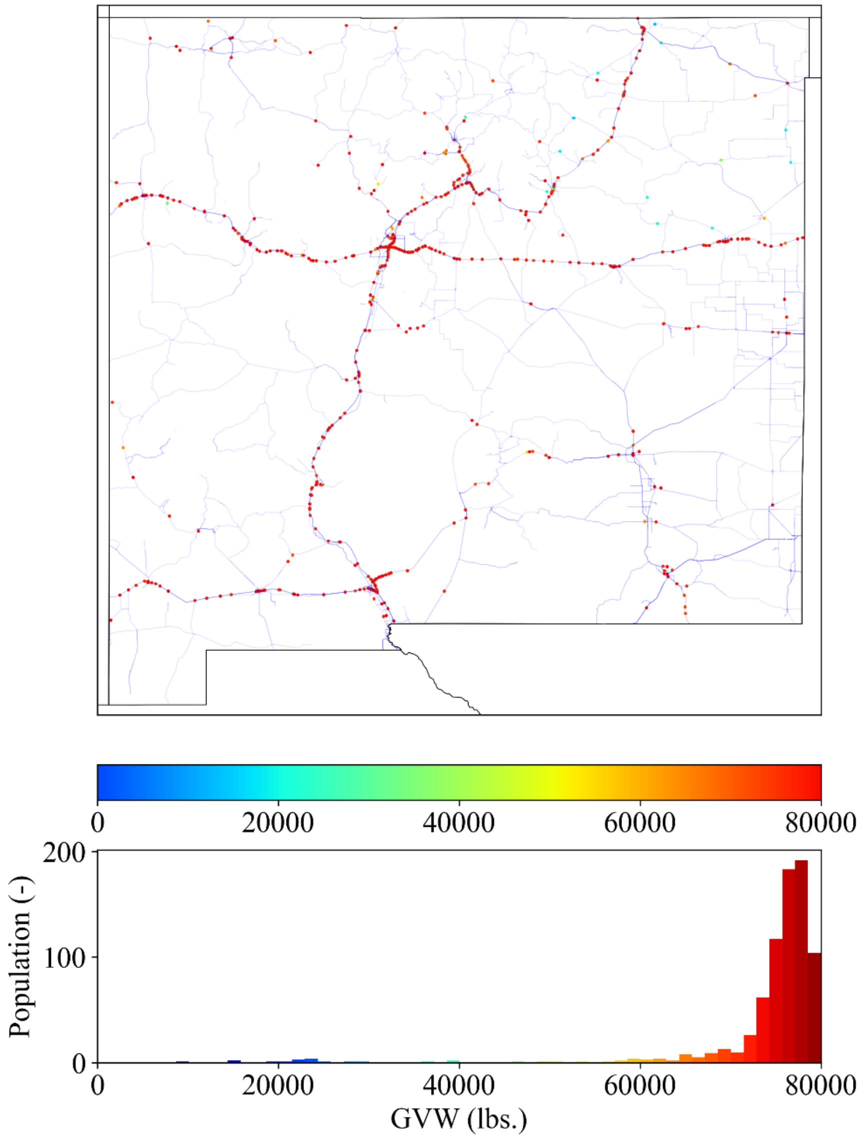

Figure 55. Average GVW for vehicles with OS permit (lbs.)

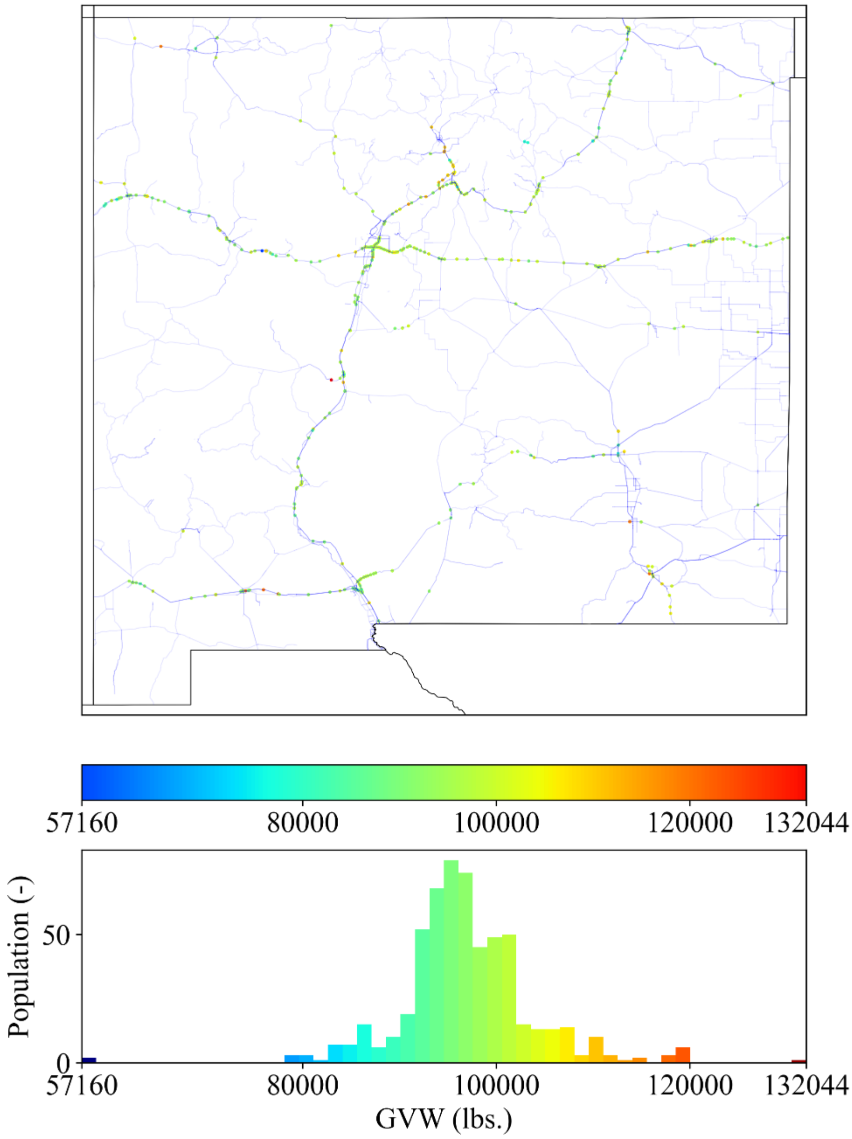

Figure 56. Average GVW for vehicles with OW permit (lbs.)

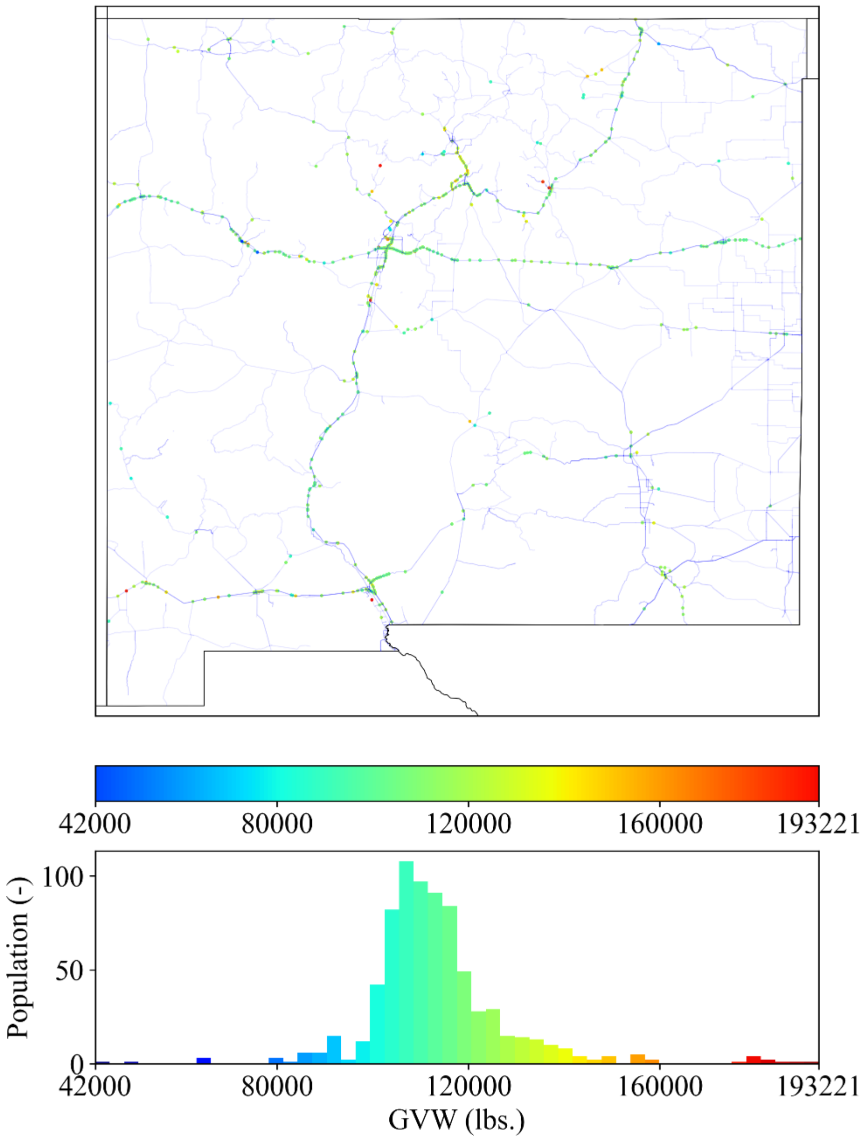

Figure 57. Average GVW for vehicles with OS/OW permit (lbs.)

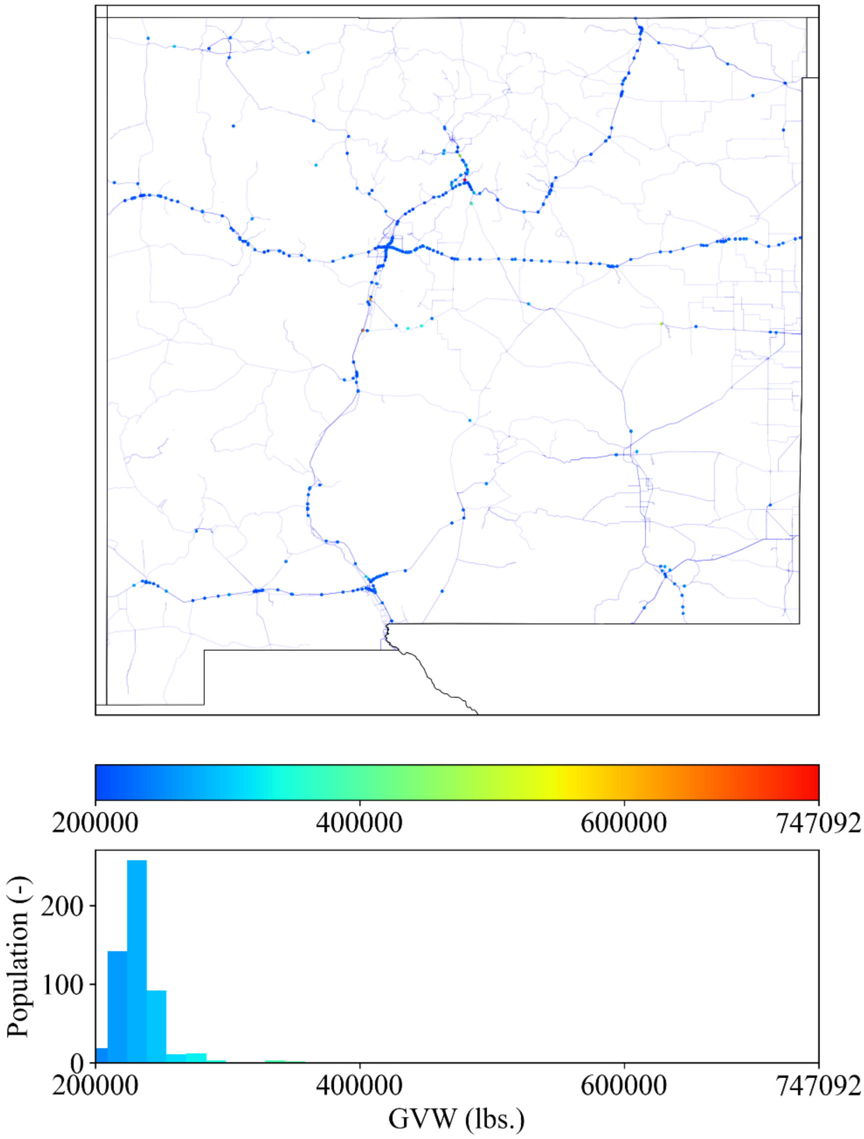

Figure 58. Average GVW for vehicles with super load permit (lbs.)

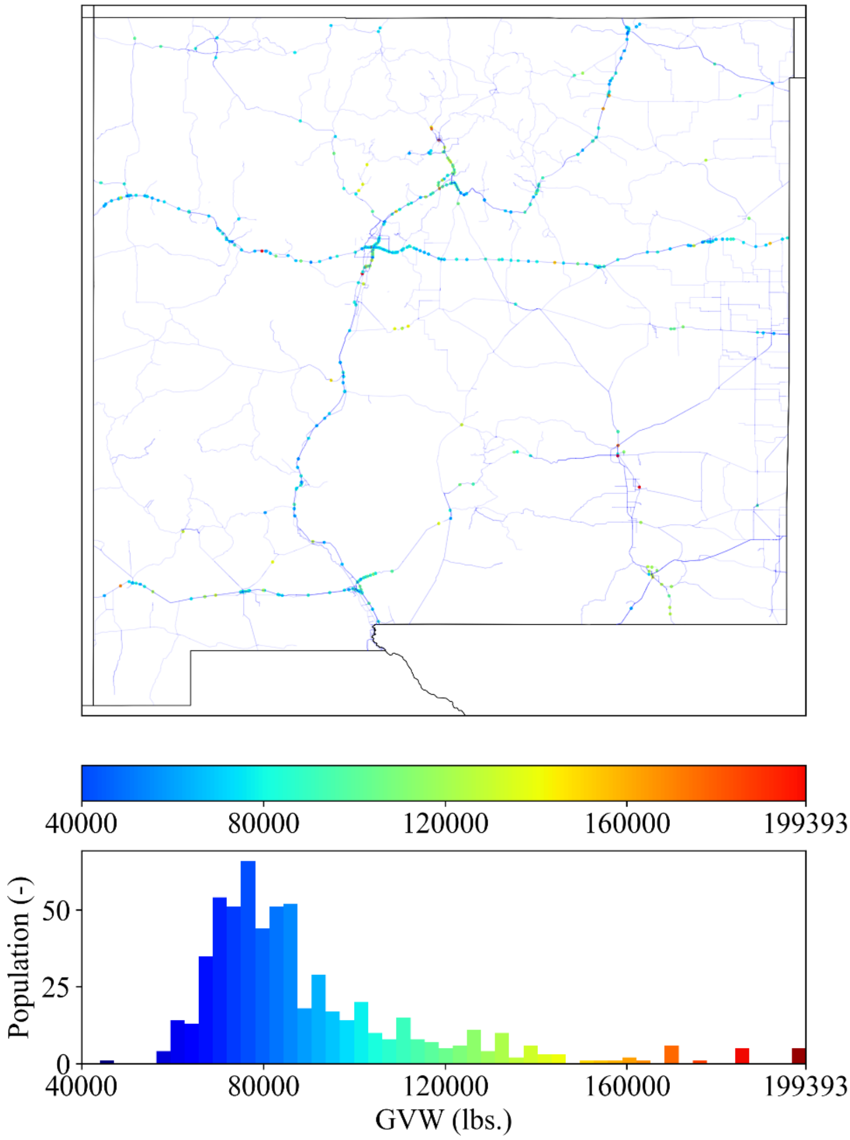

Figure 59. Average GVW for vehicles with self-propelled permit (lbs.)

4.4. Feature selection

Feature selection and extraction are popular methods for identifying a subset of important features, or their combinations, from a dataset (such as the NBI) that are the most informative or explanatory in a predictive model. In this section, the most important features from the NBI dataset and OS/OW dataset were determined using a Random Forest (RF) algorithm. The RF algorithm is an ensemble learning method that was initially developed by Breiman [59] and an advantage of the method is that it is invariant with respect to scaling. The method builds multiple decision trees using randomized samples by replacing the equivalent size of the training set. Each tree is trained using limited sets of features that are randomly selected. Unknown test data are then classified according to the highest vote among all decision tree classifiers. Decision trees can grow on a very large scale. To overcome this issue, it is common to set a threshold for the number of features used to train the model which is usually the square root of m, the total number of features [59]. However, all features are likely to be used in separate trees and thus, all will contribute to training the model.

Before the feature selection, the ADPT and average GVW values for the OS/OW permit loads for each bridge were first added into the NBI dataset. The RF algorithm was then applied to the modified NBI dataset and the selected features (34 total) are reported in Table 31.

Table 31. Selected features using the RF algorithm.

Selected features names	
ROUTE_PREFIX_005B	KILOPOINT_011
DETOUR_KILOS_019	MAINTENANCE_021
OWNER_022	FUNCTIONAL_CLASS_026
YEAR_BUILT_027	ADT_029
APPR_WIDTH_MT_032	DEGREES_SKEW_034
STRUCTURE_KIND_043A	STRUCTURE_TYPE_043B
MAIN_UNIT_SPANS_045	HORR_CLR_MT_047
MAX_SPAN_LEN_MT_048	STRUCTURE_LEN_MT_049
ROADWAY_WIDTH_MT_051	DECK_WIDTH_MT_052
VERT_CLR_UND_054B	OPERATING_RATING_064
INVENTORY_RATING_066	APPR_ROAD_EVAL_072
WORK_PROPOSED_075A	WORK_DONE_BY_075B
IMP_LEN_MT_076	DATE_OF_INSPECT_090
YEAR_RECONSTRUCTED_106	FUTURE_ADT_114
LOWEST_RATING	DECK_AREA
ADPT	Average GVW
STRUCTURAL_EVAL_067	DECK_PROTECTION_108C

Subsequently, the ADPT, annual average GVW, and selected NBI features were used as inputs to the data-driven model; the main goal is to classify the bridge condition ratings which are the model outputs. Machine learning (ML) involved the application of computer algorithms for classification purposes through a training process. In this study, two supervised ML algorithms are used to build a model based on sample data (known as training data) to predict the bridge conditions. The predictive model can be used in a life-cycle analysis to determine the reduction in bridge service life as a result of OW trucks. In turn, the service life reduction can be used in a cost analysis to calculate the damage cost imposed by OW trucks (see Figure 39).

4.5. Leveraged ML classifiers

Two different classifiers were used to design the predictive models: (1) Support Vector Machine (SVM) with linear and Radial Basis Function (RBF) kernels, and (2) Gradient Boosting Decision Tree (GBDT). In the next sections, these classifiers are briefly discussed.

4.5.1 Support vector machine

SVM is a popular learning algorithm proposed by Vapnik [46] that has been previously applied to several real-world problems such as image classification [46][54], text categorization [61][72], handwritten character recognition [43], and gene / protein classification [58][63][78]. The initial version of SVM was solely capable of performing binary classification tasks, but newer variants were later developed for multi-class classification.

Kernel-based SVMs were primarily developed for problems that are not linearly separable [49]. The goal of using kernel functions is to transform the data into a higher-dimensional feature space so the problem becomes linearly separable. The idea behind the SVM algorithm is to find an optimal hyperplane that separates the two classes with the maximum margin. Assume that a set of training samples is represented by

$$\{(x_i, y_i)\}_{i=1}^{l}, \qquad x_i \in R^N, \qquad y_i \in \{-1,1\} \qquad \text{Eq. 27}$$

where *n* is the number of samples and *m* is the size of the feature set. The SVM method solves the following optimization problem [48]:

$$\min_{w,b,\xi} \frac{1}{2}\omega^T\omega + C\sum_{i=1}^{l}\xi_i$$
$$\text{s.t.} \quad y_i(\langle\omega, \phi(x_i)\rangle + b) \geq 1 - \xi_i\,,\ i = 1, \dots, n \qquad \text{Eq. 28}$$
$$\xi_i \geq 0\,,\ i = 1, \dots, n$$

where ϕ is the kernel function that is necessary to map each training sample into a higher-dimensional space. Parameter C is a positive tuning parameter specified by the user. This parameter controls the trade-off between the margin maximization and misclassification penalty. SVM is often solved by taking the Lagrangian dual of a mathematical program (Eq. 28) with the Kuhn–Tucker conditions, which yields a convex quadratic program as follows:

$$\max_{\alpha} \sum_{i=1}^{n}\alpha_i - \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\alpha_i\alpha_j y_i y_j K(x_i, x_j)$$
$$\text{s.t.} \quad \sum_{i=1}^{l} y_i\alpha_i = 0, \qquad i = 1, 2, \dots, n \qquad \text{Eq. 29}$$
$$0 \leq \alpha_i \leq C,\ i = 1, 2, \dots, n$$

where $K(x_i, x_j) = \phi(x_i)\,\phi(x_j)$ is the kernel function used to calculate the similarity between two data samples. Once the optimal solution (w_0, b_0) is determined using the problem formulation, the class y_{new} of an unknown sample x_{new} is computed as:

$$y_{new} = f(x_{new}) = \text{sign}\,(\langle w_0^T, \phi(x_{new})\rangle + b_0) = \text{sign}\,(\sum_{i=1}^{n}\alpha_i y_i K(x_{new}, x_i) + b_0) \qquad \text{Eq. 30}$$

4.5.2 GBDT

GBDTs are ensemble models that link weak learners to make strong classifiers. They optimize the classification accuracy of the model by successively linking new trees and optimizing the following function [59]:

$$F(X) = \sum_{m=1}^{M}\beta_m h(X; a_m) \qquad \text{Eq. 31}$$

where $\beta_m h(X; a_m)$ is the base learner which in this report was selected to be a decision tree. β_m is approximated by minimizing the following loss function:

$$L(y, F(X)) = (y - F(X))^2 \qquad \text{Eq. 32}$$

It is important to mention that GBDTs are vulnerable to overfitting and their parameters should be optimized to avoid overfitting.

4.6. Results and discussion

This section provides a comprehensive discussion about the classification results and metrics. To evaluate the classification models, four important metrics for each classifier were calculated (True Positive Rate (TPR), False Positive Rate (FPR), True Negative Rate (TNR), and False Negative Rate (FNR)) as follows:

$$TPR = \frac{TP}{TP+FN} \quad \text{Eq. 33}$$

$$TNR = \frac{TN}{TN+FP} \quad \text{Eq. 34}$$

$$FPR = \frac{FP}{FP+TN} \quad \text{Eq. 35}$$

$$FNR = \frac{FN}{FN+TP} \quad \text{Eq. 36}$$

In statistics, a false positive result indicates a given condition exists when it, in fact, does not while a true positive indicates a given condition exists when it actually does. A false negative result wrongly indicates that a condition does not hold while a true negative correctly indicates that a condition does not hold. These results are used to evaluate the accuracy of the ML algorithms in classifying bridge deck condition based on the input data. To train and test the models, 70% of the data were randomly selected for training purposes and 30% were selected for testing the models.

The GBDT classifier's hyperparameters were optimized by applying the grid search algorithm. In this context, the learning rate (η) was set equal to 0.1, the maximum depth of trees was calculated as 7, and 500 boosting stages were used as optimized GBDT classifier parameters. The classification results using the algorithms and selected features (provided in Table 31) are displayed in Table 32.

Table 32. Classifiers' performance for classifying bridge condition ratings.

		Deck	**Superstructure**	**Substructure**
SVM (Linear)	TPR	0.6333	0.6857	0.7825
	TNR	0.9476	0.9651	0.9758
	FPR	0.0524	0.0349	0.0241
	FNR	0.3667	0.3143	0.2175
SVM(RBF)	TPR	0.6270	0.6739	0.7780
	TNR	0.9467	0.9638	0.9753
	FPR	0.0533	0.6458	0.0247
	FNR	0.3730	0.3261	0.2220
GBDT	TPR	**0.9531**	**0.9670**	**0.9650**
	TNR	**0.9948**	**0.9959**	**0.9961**
	FPR	**0.0052**	**0.0041**	**0.0039**
	FNR	**0.0469**	**0.0330**	**0.0350**

According to Table 32, the GBDT classifier performs the best since the TPR and TNR values are relatively higher than those for the SVM classifiers indicating that the GBDT classifier has a lesser degree of misclassification. To provide better insight into the classification results, confusion matrices are displayed in Figure 60. The large values for TPR and TNR, for example, indicate a high likelihood of correctly classifying the bridge conditions using the input data. The small values of FPR and FNR, on the other hand, indicate a low likelihood of misclassification by the algorithm.

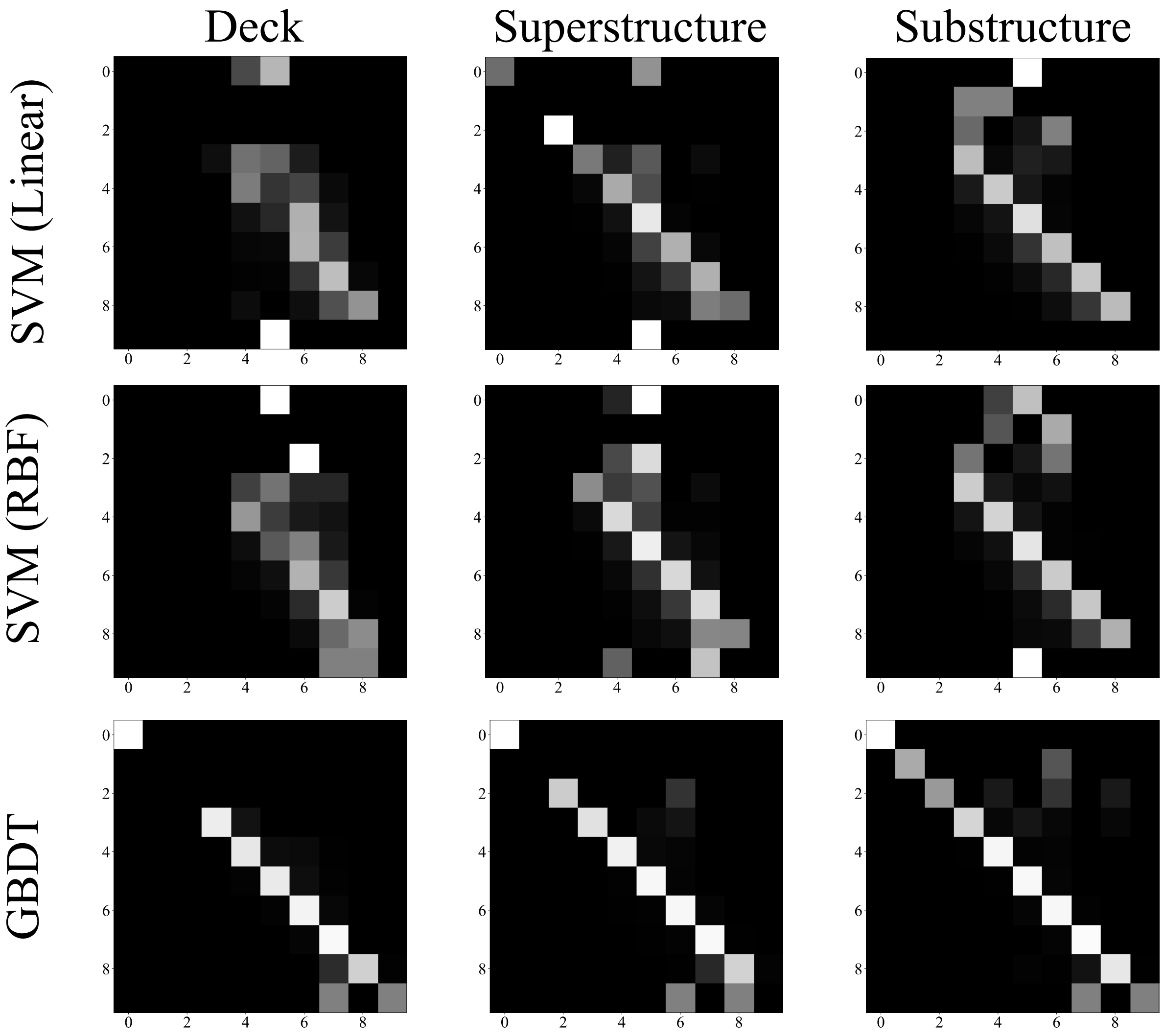

Figure 60. Confusion matrices for classifiers.

In the confusion matrices, black represents zero and white represents 1 since it is a greyscale image. Hence, a classifier with a confusion matrix that has a bright diagonal line is performing satisfactorily. Figure 60 shows that GBDT has a small degree of misclassification (bright cells are located mainly on the diagonal) while SVM classifiers have severe misclassification. It should be noted that SVM misclassified bridges with low condition ratings as ones with high condition ratings which is problematic. This misclassification does not appear in the GBDT confusion matrix.

To assess the performance of the classifiers on new data, the classifiers were first trained based on available data from 2016 to 2020 and then tested on data from 2021. The main goal for this exercise was to investigate the performance of the GCDT on data that has not been analyzed by the classifier. Accordingly, the 2021 NBI dataset was integrated with the OS/OW dataset from 2020. Table 33 and Figure 61 shows the GBDT performance in classifying the 2021 bridge condition ratings. It can be seen that the GBDT classifier reached a high accuracy for the dataset that was not used to train the classifier. Although the accuracy dropped about 2%, the performance of the classifier is still satisfactory.

Table 33. GBDT classifier's performance in classifying 2021 bridge condition ratings.

		Deck	Superstructure	Substructure
GBDT	TPR	0.9370	0.9229	0.9315
	TNR	0.9921	0.9903	0.9914
	FPR	0.0079	0.0097	0.0086
	FNR	0.0630	0.0771	0.0685

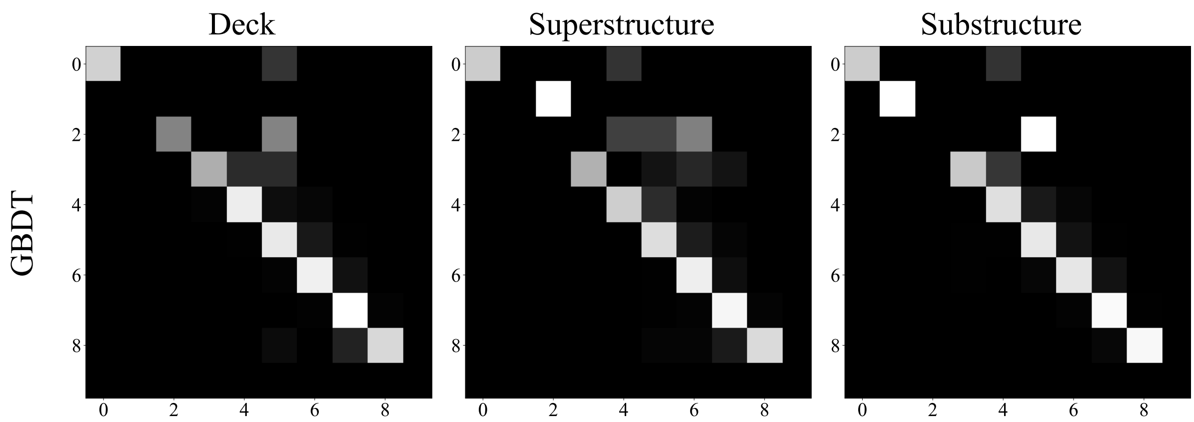

Figure 61. Confusion matrices for the GBDT classifier for the 2021 dataset

Figure 61 shows the confusion matrices for the GBDT classifier for the 2021 dataset and some misclassifications are apparent; however, the performance of the classifier is still promising since the main diagonal lines are bright and close to 1. The reported 2021 results are important since they provide evident that the trained model can be used with confidence for different years. If the classifier is updated on a yearly basis, the accuracy further improves. As a result, this would help with risk-based scheduling of bridge inspection intervals. Finally, the model can be used for life-cycle and cost analysis purposes (see Figure 39) to determine the additional cost per mile associated with bridge damage caused by OW trucks. This additional cost per mile can be added to the cost per mile of OW damage to pavements.

5. CONCLUSIONS

This final report presented the results for Tasks 1 through 3. In the first task, a data-driven approach was proposed and employed to determine the most common oversize/overweight (OS/OW) scenarios in the state of New Mexico based on available data. The most common OS/OW truck configurations and vehicular routes were identified for each permit category. The main features considered to identify the most common trucks and routes are GVW, distance traveled, and axle weights and spacings. Permit fee data for a time span of almost three years (Jan 2016-Aug 2018) provided by the ProMiles Software Development Corporation were used. After cleaning the data, the research team developed and employed a rigorous statistical framework to identify the most frequent permit vehicles traveling through New Mexico and associated routes. Using the framework, seven scenarios were identified and approved by the NMDOT Technical Panel. Three separate vehicles identified by the NMDOT Bridge Bureau were also included for a total of ten representative cases for consideration in the cost analysis conducted in Task 2.

In Task 2 the research team assessed the differences in fees charged for similar OS/OW load configurations and route types across Arizona, Colorado, Oklahoma, and Texas. The ten cases identified in Task 1 were used to quote permits from neighboring states. It was found that New Mexico charges the lowest fees of all five states in all but one case. In six of the ten cases Oklahoma is the highest charging state. Most of the fees charged by Texas are above average and are close to the permit costs in Oklahoma. The fees charged by Arizona and Colorado are more comparable to the current fees in New Mexico; however, overweight traffic demand in South Eastern New Mexico is similar to that in Texas. In fact, Colorado does not even permit super heavy load cases. Modest increases in the flat fees for single trip and annual OS/OW vehicle permits in the state would bring the state costs more in par with fees in Oklahoma and Texas without exceeding four state averages while helping secure an additional \$6.6 to \$10 million in yearly revenues for investment in transportation infrastructure impacted by overweight vehicle traffic in New Mexico. Increasing the current overweight mileage surcharge and instituting a new excess axle group weight mileage surcharge would bring the permit fees for super heavy loads closer to those charged in Texas and Oklahoma.

In Task 3 for pavements, the research team conducted a review of the literature to identify relevant methods employed in the analysis of damage to pavement structures. The different methods were grouped into fixed vehicle analysis and fixed traffic analysis. Simplifying assumptions made in each method were discussed as well as the information requirements related to the axle load configuration and the pavement structure. Understanding information requirements is critical in the development of a suitable framework of analysis. If the information needed is already collected and curated, the implementation of the damage assessment can be straight forward. However, if information gaps exist, a plan will be needed to obtain it. Fixed vehicle analysis using the AASHTO equivalent axle load factor method was introduced as a realistic entry point for the development of a damage-based fee assessment for OW vehicles. To demonstrate this, the team used equivalent axle load factors to compare the damage caused by the 10 different OS/OW vehicle cases identified in Task 1 on a given pavement structure. The results of the fixed vehicle damage analysis show that the axle configuration and axle loading in case 3 cause the most damage to the pavement structure. Even though the GVW in case 3 (225 kips) is below that of cases 2 (246 kips), 8 (324 kips), 9 (255 kips), and 10 (304 kips). Juxtaposition of the damage and permit fees for each case shows that despite of the differences in the magnitude of the fees charged by the five states, the fees seem to track the effect of gross vehicle weight as opposed to cumulative axle damage. Cases 2, 3, 8, 9, and 10 are charged similar fees even though there is a substantial difference in the damage caused by each. In all cases, states fail to assess a higher fee to the vehicle that causes the most damage (Case 3) while charging more to other vehicles (Case 2 and Case 9) based on their relative damage.

In Task 3 for bridges, the research team surveyed the state-of-the-practice and the state-of-the-art methods for overweight damage characterization of bridges. Over the past 20 years, the DOTs in several states including AZ, IL, LA, NY, SC, TX, and WI have performed studies to evaluate the bridge damage caused by OW vehicles and the associated costs. All of these state DOTs used OS/OW vehicle data (from the permitting office and/or WIM stations) together with NBI data (ranging from less than 4 to more than 20 features) for the damage evaluation. Although only a few states actually developed a new permit fee structure, it was found that a data-driven approach is essential to understanding the impact of different factors on bridge deterioration. Finally, the approach can help to determine the damage costs associated with OS/OW vehicles so the appropriate fees can be charged. Consequently, the available NBI and permit datasets were comprehensively analyzed for New Mexico. The permit dataset was used to calculate the load frequency and load intensity for each OS/OW permit type and the NBI dataset was used to compute changes in the bridge condition ratings. By correlating the rating differences with the OS/OW load information, critical travel zones in New Mexico where the bridge conditions were impacted the most by permit loads were identified. The NBI and permit load datasets were then used to develop a simplified data-driven model to predict the condition ratings of bridges. In the first step, a feature selection was perfumed using the Random Forest (RF) method to identify the most influential features in the NBI dataset. In the second step, two different machine learning algorithms were used to design the predictive models: (1) Support Vector Machine (SVM) with linear and Radial Basis Function (RBF) kernels, and (2) Gradient Boosting Decision Tree (GBDT). The GBDT classifier performed the best in terms of predicting the condition ratings. As a result, the approach could assist the NMDOT with risk-based scheduling of bridge inspection intervals. The model could also be used in to predict which bridges are most prone to future damage due to OS/OW trucks and determine the additional cost per mile needed to repair or replace these bridges. This additional cost per mile can then be added to the cost per mile needed to recover the damage caused to pavements.

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