Louisiana Transportation Research Center

Final Report 616

Transportation Infrastructure Asset Damage Cost Recovery Correlated with Shale Oil/Gas Recovery Operations in Louisiana

by

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16. Abstract

The rapid growth of shale gas exploration imposed a large number of heavy truck trips on Louisiana roadways. It is necessary to estimate the impact of the shale-gas related traffic. This study aimed estimate the impact of the shale-gas related overweight truck trips on Louisiana roadways at the network and project level. RStudio software was employed to extract and reformat the overweight trips in the Haynesville area in 2006-2016 from the oversize/overweight (OS/OW) database. Network Analyst in the ArcGIS was utilized to assign these extracted overweight trips directly on the roadway network according to the shortest path method. The vehicle miles travelled (VMT) in terms of roadway classifications were estimated subsequently. In total, there were 9.7 million shale-gas related overweight VMT in 2006-2016, which translates into a damage cost of $17 million. On average, the damage cost due to the overweight trips in the construction of a single well approximates $5,264 and the damage cost per overweight vehicle travelling in one mile approximates $1.74. Due to the limitation of network-level analysis, project-level analysis was also conducted to quantify the damage cost due to overweight truck trips generated from shale gas recovery activities. The impacted area was divided into zones and overweight truck trips were estimated based on the numbers of wells and traffic interaction among zones. The AASHTOWare was adopted to obtain the pavement distress, and the results were matched to data collected from Pavement Management System (PMS). Then scenarios with no overweight truck loads were simulated to obtain the difference of service lives with/without shale gas truck traffic. EUAC method was applied to calculate the damage costs of overweight truck trips, and damage costs for various truck gross weight levels for Louisiana low volume routes were obtained thereafter. The equipment trucks with gross vehicle weight (GVW) from 80-200 kips used in oil-gas industry were investigated. A permit fee regulation was recommended considering GVW and travelled distance to update the current one used by DOTD.

17. Key Words
Hayneville Shale; Overweight trips; Damage cost; Shale gas well; RStudio; ArcGIS; MEPDG; Permit fee

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ABSTRACT

The rapid growth of shale gas exploration in the area of the Haynesville Shale formation has imposed a large number of heavy truck trips on Louisiana roadways. It is necessary to estimate the impact of the shale-gas related traffic. Previous studies investigated the overall impact of the shale gas development on infrastructures without differentiating overweight trips and non-overweight ones. This may result in difficulty in the damage cost recovery of those overweight trips through issuing overweight permits. In addition, the truck trips in previous studies were distributed either based on assumed origins/destinations with a limited number or simply based on the mileage percentages of different roadway classifications in the network. These assumptions may not reveal the actual situation. Therefore, this study aimed to overcome these disadvantages and estimate the impact of the shale-gas related overweight truck trips on Louisiana roadways at the network level. RStudio software was employed to extract and reformat the overweight trips in the Haynesville area in 2006-2016 from the oversize/overweight (OS/OW) database. Network Analyst in the ArcGIS was utilized to assign these extracted overweight trips directly on the roadway network according to the shortest path method. The vehicle miles travelled (VMT) in terms of roadway classifications were estimated subsequently. In total, there were 9.7 million shale-gas related overweight VMT in 2006-2016, which translates into a damage cost of $17 million. On average, the damage cost due to the overweight trips in the construction of a single well approximates $5,264 and the damage cost per overweight vehicle travelling in one mile approximates $1.74. These average costs may serve as a reference for the future damage cost recovery.

Due to the limitation of network-level analysis, project-level analysis based on the 12 damaged routes in Haynesville area was also conducted to quantify the damage cost from overweight truck trips generated from shale gas recovery activities. The impacted area was divided into15 shale-gas well zones and an interaction matrix was developed by summarizing the roadway relationships among zones. Based on this matrix approach, the overweight truck trips on these damaged routes were estimated. The details of the selected roadways such as pavement structures, design traffic, and construction date were collected from the Pavement Content Manager. The Pavement ME was adopted to obtain the pavement distress due to shale gas development, and the results were matched to data collected from Pavement Management System (PMS). Then scenarios with no overweight truck loads were simulated to obtain the difference of service lives with/without shale gas truck traffic. Life cycle analysis was applied to obtain the damage costs of overweight truck trips for the 12 Louisiana low volume routes. Another approach with AASHTO 93 was also conducted to estimate the project level damage cost. The equipment trucks with various GVWs were investigated considering DOTD regulation about axle configurations. The damage cost per truck mile on GVW ranges within 80-252 kips were obtained, and a new permit fee regulation involved GVW and travel distances following the current overweight truck permit fee schedule was suggested. In addition, single trip permit and annual permit with various GVW levels are also recommended.

ACKNOWLEDGMENTS

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IMPLEMENTATION STATEMENT

This research project developed a network level analysis method to estimate the traffic impact of overweight truck traffic on Louisiana roadways, which is based on overweight/oversize permit database and ArcGIS. This method is convenient for summarizing the vehicle miles travelled (VMT) into desired roadway categories and therefore the damage cost for each roadway type could be obtained correspondingly. It is recommended that DOTD adopt this method for analysis of other permit types such as seasonal agricultural activities, oversize trips, etc.

In addition, a new permit fee schedule considering gross vehicle weight (GVW) and travelling distance is recommended, based on the damage costs obtained from project level analysis on LA low volume routes (AADT<2000) and the statistic from network level analysis. It is suggested that DOTD consider this permit fee schedule in making overweight truck related policy.

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INTRODUCTION

Problem Statement

At present, the shale oil/gas recovery activities are under development in three major shale plays in Louisiana, as shown in Figure 1 [1]. Out of them, Haynesville shale play experiences most of the activities regarding shale gas recovery, as shown in Figure 2. Due to the drilling and operating of the shale oil/gas wells, a large number of truck trips are required for transporting equipment and materials, hauling fresh water, and disposing salt water to and from the shale oil/gas recovery sites. As a result, roads and bridges that were designed for agricultural purposes and/or residential accesses are now subjected to heavy traffic loads that are far beyond the original design limits of the infrastructures. It has been noticed that the transportation infrastructure damages in northwest Louisiana due to oil/gas recovery activities have been increasing drastically. However, there is no existing approach available for Louisiana to estimate the damage costs and recover the costs from the oil/gas industries. Therefore, it is necessary for the Louisiana Department of Transportation and Development (DOTD) to assess the infrastructure damage costs so that the damage costs can be recovered from the oil/gas industries.

Figure 1
Shale plays in Louisiana [1]

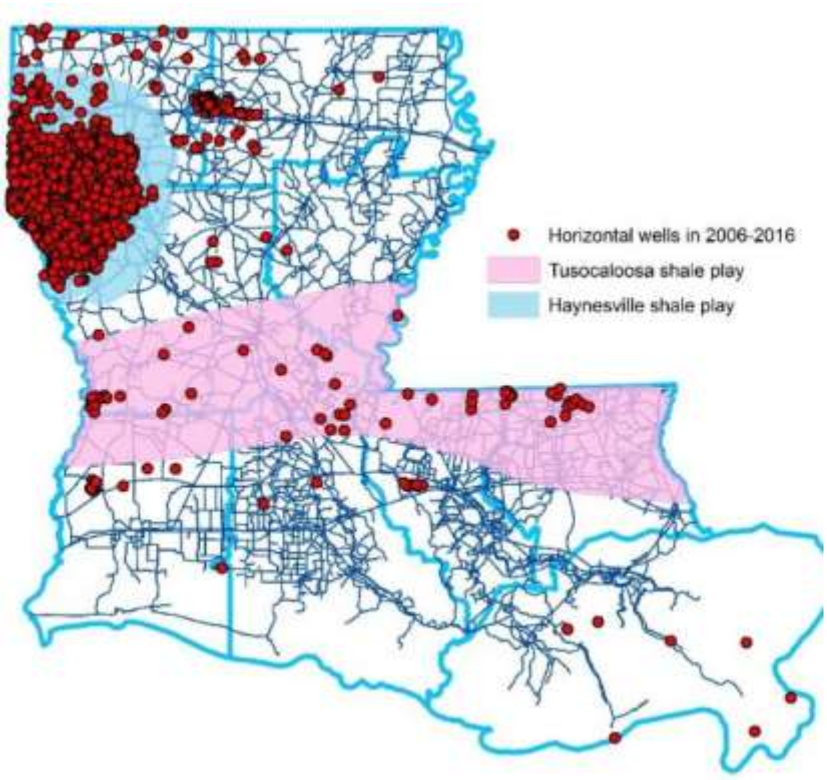


Figure 2
Shale gas wells throughout the state

Literature Review

The development of drilling technology of oil/gas wells led to mass consumption of petroleum. These versatile fossil fuels influence daily life deeply and considerable efforts have been made to expand the supply of fossil fuels for the growth of economy. The production of oil/gas from shale formations has revitalized the oil/gas industry in the United States due to the new developments in horizontal drilling and hydraulic fracturing. The shale oil/gas development activities require large volumes of heavy trucks over rural roads for the transportation of supplies, such as heavy equipment, fracking sands, fresh water and waste water, to and from the location of these activities.

Shale Gas

Shale is a type of fissile rock comprised of laminated layers of clay-like and fine grain sediments. It is mainly composed of the consolidated mud or clay and organic carbon. Natural gas that is trapped within shale play is referred to as shale gas. Shale plays are shale formations containing significant accumulations of natural gas. Figure 3 shows the major shale plays in the United States [2]. Haynesville shale play, located in areas of Texas and Louisiana, is one of the significant shale plays in Louisiana and the major area investigated in this study. Tuscaloosa shale play is a prospective shale play and this area will be investigated as well for the forecast of the impact on roadways due to the future shale oil/gas development.

Figure 3
Major shale plays in the United States [2]

Overview of Well Development

The five stages in the development and operation of an oil/gas well are summarized below [3]:

- Leasing and exploration—Geologists and petroleum engineers will target an area for exploration and the oil company representatives will negotiate with property owners to acquire leases. With the mineral rights secured, energy companies need to get permission for a drilling plan.
- Pad construction—The second stage of the well development is the pad construction. In this process, a gravel road will be built and a pad site with 3 to 5 acres will be graded. Some pad sites contain multiple wells. The construction of the road and pad requires large amount of equipment, materials, and truck trips.
- Drilling—In this stage, the drilling rig will drill a well into the shale layer vertically and continue horizontally in the direction of the intended extraction location. During the process, the transportation of drilling fluid, equipment, sands, casings and pipes

implies a large volume of truck trips. Four to six weeks are necessary for the drilling of one well.

- Completion—Hydraulic fracturing (fracking) is conducted in this stage. Fracking provides additional permeability in the producing formation. After the drilling stage, the drilling rig is replaced with a multitude of hydraulic fracturing equipment, including blender trucks, pump trucks, water tanks, flowback water trucks, and fracture sands. In this completion stage, firstly, a fracking gun is used to penetrate through the well casing and fracture the shale at the furthest depths of the well. Secondly, a highly pressured mixture of water and proppant is pumped into the fractures to crack the shale along its natural weaknesses. Sand mixture is usually used in the proppant to keep the cracks open and help the oil/gas escape from the shale. Then, fracking will be conducted along the whole horizontal well. Figure 4 illustrates the scenario of the fracking [4]. In this stage, a large number of truck trips are needed primarily due to the volume of water needed in fracking the wells and the disposal of flowback water.

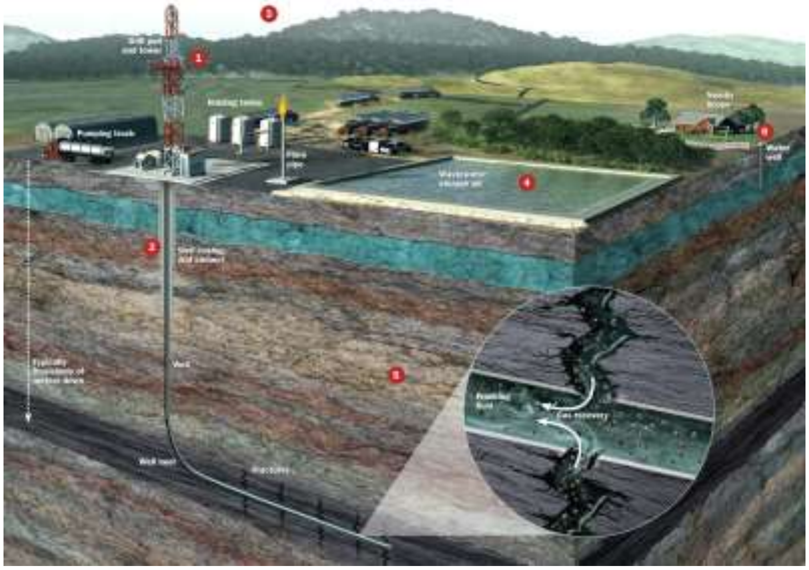


Figure 4
Fracking [4]

- Production—This stage requires the removal of fracking machinery, the installation of production equipment, and pumping produced water from the well for disposal. The production traffic is mostly salt water trucks used to move the saltwater from the well site to the nearest injection well [5]. During this stage, the number of truck trips drops significantly to approximately two trips per day.

Transportation Demands

Figure 5 shows the top view of a typical well pad for the shale oil/gas recovery [6]. The figure demonstrates that different types of the truck traffic are needed under different stages. The major amount of traffic volume is contributed by rigging movement, water transported to well sites, and disposal of water from the sites. Additionally, the transportation demand for the shale oil/gas development varies in different stages.

Figure 5
Top view of a well pad [6]

Many studies have been conducted to evaluate the trip generated by the energy development activities. A study conducted by the Texas State Department of Highways and Public Transportation in 1980s estimated that drilling a single well takes about 60 days and 1365 truck trips [7]. NCHRP reviewed the energy development in different states [8]. It pointed out that a vertical well generates approximately 1,100 equivalent single axle loads (ESALs). In New York state, 1,148 one-way loaded truck trips are generated for hauling of water per well [9]. The drilling of each well requires 1,800 ESALs with piping and 2,800 ESALs without piping to the water wells. Another study conducted in North Dakota estimated that each well generated an average of 2024 rig-related truck trips [10]. Based on the information of various loads (e.g., equipment, water, etc.) hauled to and from the wells, origin-destination estimates of traffic on the local roads were performed.

In a study conducted by the firm Felsburg, Holt, and Ullevig, multiple national and regional studies examining truck trips in the well development phase were reviewed and the truck trip data were summarized, as shown in Table 1 [3]. In the study, the truck trips in the production stage were estimated as two trips per day per pad. The trips shown in Table 1 include both the inbound and outbound trips.

Table 1
Summary of the trip generation per well under construction stage [3]

Phase		NPS 2008	NTC 2011	NTC 2009	UDOT 2006
Construction	Pad and road construction	55	180	56	55
Drilling	Drilling rig	60	190	60	60
	Drilling fluid and materials	75	90	75	30
	Drilling equipment	75	190	75	—
Completion	Completion rig	30	—	30	65
	Completion fluid and materials	30	40	30	70
	Completion equipment	10	10	10	—
	Fracturing equipment	250	350	350	—
	Fracture water	1052	1000	1000	1100
	Fracture sand	48	46	45	52
	Flowback water disposal	—	200	500	—

Impact of the Extra Truck Trips on Roadways

With the increase of the truck trips due to the energy development, roadways will be influenced. According to a NCHRP study [8], 32 DOTs indicated that roads have been impacted by all kinds of energy development activities. Table 2 shows the number of DOTs that rated the severity of the impact of energy development. It is clearly noted that local roads were severely impacted by the energy development activities as compared with other types of roads such as interstate roads.

Table 2
Number of DOTs that rated the impact of energy development (NCHRP 2015)

Roadway type	Number of DOTs in 31 DOTs			
	No Impact	Minimally impacted	Moderately impacted	Significantly impacted
Interstate	10	16	2	3
Primary (National or state highway)	4	13	11	3
Secondary	2	8	14	7
Secondary (local roads)	2	9	10	10

Transportation Modeling

Transportation (freight) modeling consists of various components, including planning, economy, and logistics, etc. A thorough literature review identifies different transportation models, which include link-level factoring method, factored truck trip table, commodity-based freight model, three-step model, hybrid model, supply chain and logistics chain model, and tour-based model.

Three-step modeling is generally used for the analysis of transportation of shale oil/gas development activities, including trip generation, trip distribution, and trip assignment [5, 11].

- Trip generation—Trip generation requires the identification of traffic to and from the well construction sites on shale plays. The analyzed area can be divided into traffic analysis zone (TAZ) depending on the geographical or development scenario. The trip generation requires the inventory analysis of the existing number of wells in the TAZs and the number of trips generated by each well.
- Trip distribution—Trip distribution requires the distribution of the trips between origins and destinations for each TAZ. The origin-destination database will be developed in this step. Figure 6 shows a typical origin-destination relationship for shale oil/gas development activities. In previous studies regarding the impact of the shale oil/gas development on roadways [5, 11], the establishment of the origin-destination relationship was typically based on the criterion of shortest path or shortest time.

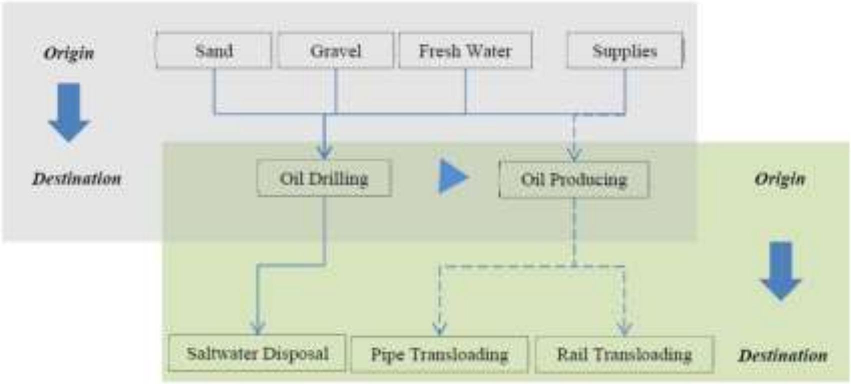


Figure 6
Origin-destination relationship for shale oil/gas development activities [11]

In the generic transportation modeling, growth factor model and gravity model are usually employed to consider the traffic growth by year and the interaction between origins and destinations.

- Trip assignment—Traffic assignment identifies the possible routes between the origin and destination in the origin-destination (O-D) database from the trip distribution step and allocating the trips on them. Traffic assignment can be done by the "user equilibrium" or "all-or-nothing" method. The user equilibrium method means the traffic has the freedom to choose any of alternative routes, through which the same duration is needed to reach destinations. The all-or-nothing method implies that traffic will choose one route that is more appropriate for freight traffic.

Pavement Analysis

The extra traffic volume generated by the oil/gas recovery activities has significant impacts on roads, especially on local roads as mentioned in previous paragraphs. DOTD has identified 26 roads as damaged in the Haynesville shale play area. Of the 26 roads, LA169 is taken as an example to demonstrate the damage. Figure 7 shows the on-site view of LA169. Figure 8 shows the distresses of Route LA169 based on the PMS database. As shown in Figure 8, the distresses of LA169 increase drastically after 2008, the beginning of the rapid blooming of shale oil/gas development activities in that area.

The damage to roads due to the shale oil/gas development activities causes the reduction the serviceable life of pavements. Pavement analyses are usually conducted to quantify the reduction of the serviceable life. The remaining serviceable life of the roads is often adopted to describe the condition of pavements. The method of the pavement analysis adopted in previous studies include AASHTO 1993 method and the Pavement ME design method [5, 12].

Based on the AASHTO 1993 design method, the serviceability index of a road with and without shale oil/gas traffic can be determined and the difference can be used to evaluate the reduced service life of the roads due to the shale oil/gas traffic. According to the Pavement ME design method, the distresses of a road with and without shale oil/gas traffic can be analyzed and the control distress will be chosen for the determination of the reduced service life of pavements.

Figure 7
On-site view of LA169 in the area of Haynesville shale play

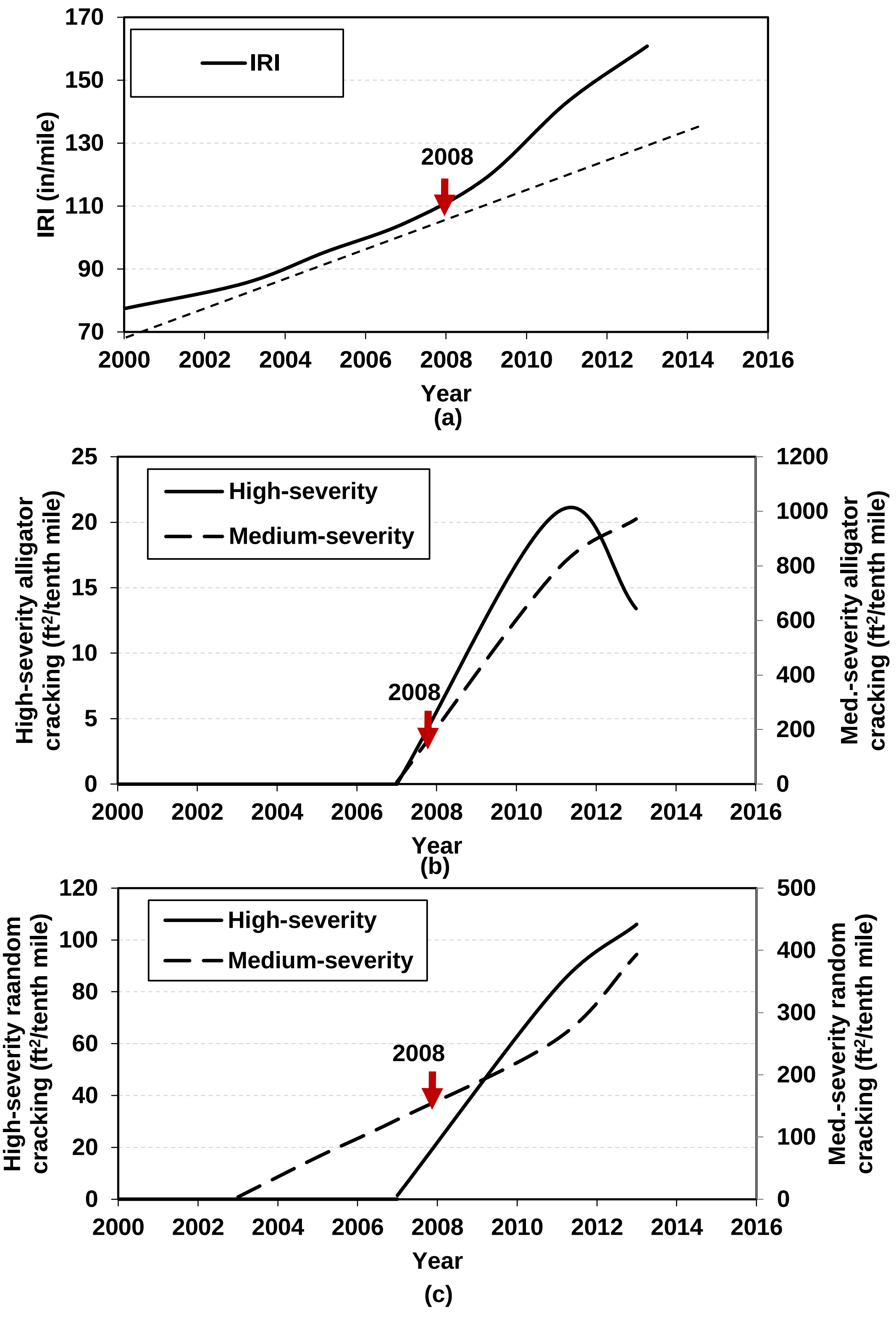


Figure 8
Distresses of LA169 with segment ID from 097011068 to 097011098: (a) IRI, (b) Alligator cracking, and (c) Random cracking

Cost Analysis

Highway cost allocation studies (HCAS) were conducted by many states in the last decades [13]. Various cost analysis methods have been developed over the years, such as the incremental method and the mixed "Federal" method.

The incremental method calculates the cost for the smallest user class and incrementally assigns additional costs to other classes. All vehicle classes share the costs for the base facility equivalent to their usage of the facility [14]. The Federal method determines cost portions attributable to individual classes and then determines the portions attributable to groups of vehicles. This method uses a "consumption" method to allocate pavement maintenance costs and uses an incremental method to allocate other costs. The Federal Highway Administration (FHWA) refined the National Pavement Cost Model (NAPCOM) for the cost analysis during the 1990s. NAPCOM attributes the different damage costs to different types of vehicles.

The aforementioned methods were developed and conducted nationally. Different states adopted those methods in their HCAS along with some new approaches, such as the simplified method, Arkansas HCAS, generalized methods, and proportional to ESALs.

The impact of the shale oil/gas development activities on roadways was usually investigated in terms of the reduction of the serviceable life. The damage cost of the reduction of the serviceable life was estimated by assuming that the cost is proportional to ESALs in previous studies [10, 12]. The damage costs per lane mile for each well or for a truck type were investigated in these studies.

Strategies for Mitigating Damages and Recovering Damage Costs

The damage incurred by the traffic due to the oil/gas development activities needs to be narrowed down by some mitigation strategies and the damage cost can be recovered through fiscal remedies. Changing traffic configurations and imposing of tolls are two common strategies to mitigate pavement damages and recovering damage costs.

- Change of vehicle configurations—The use of lift axles is able to reduce the pavement's damage by distributing the total load of the truck [15]. It enables the truck-to-carry extra load when needed and also protect the tires when the truck is unloaded. Figure 9 shows the use of lift axles in various vehicles. Saber et al. [16] studied the effect of axle loads of the traffic in the sugarcane industry in Louisiana. It was discovered that the conversion of the tandem-axle vehicle in class 9 to the tridem-axle vehicle in class 10 decreased the rehabilitation cost from \$2,072/permit/year to -\$1,243/permit/year.

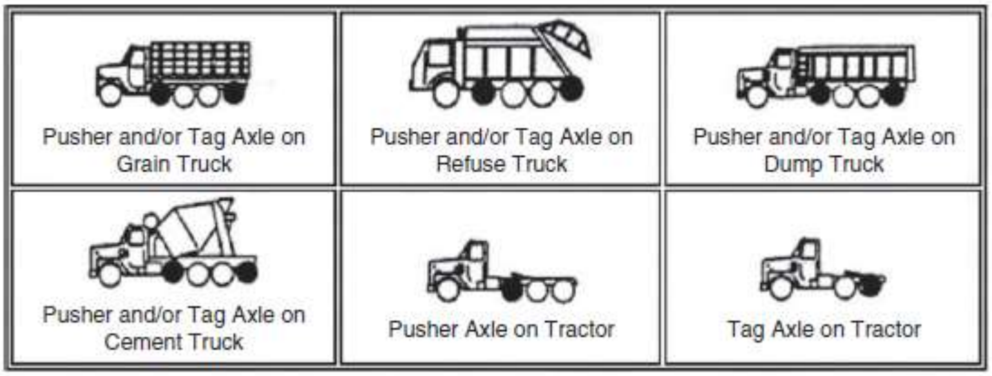


Figure 9
Lift axles in various vehicles [15]

- Tolls—Tolls can be determined on the basis of the average axle load and/or average number of axles [17]. Compared with average number of axles, the average axle load is a better reference for the determination of tolls because the impact of a vehicle on the pavement is mainly subject to the average axle load, rather than the average number of axles.
- Damage cost recovery in energy development—The most frequently reported engineering approach employed by DOTs for addressing pavement damage is to (1) increase the lane widths (and add a paved shoulder); (2) increase the pavement thickness; and (3) stabilize the surface layers of unpaved roadways. Large costs are often associated with either the rehabilitation or reconstruction of pavements. The rehabilitation costs due to the damage of energy development are typically shared by energy companies and/or state DOTs [8]. Figure 10 shows the proportion of sharing between energy companies and DOTs in different states.

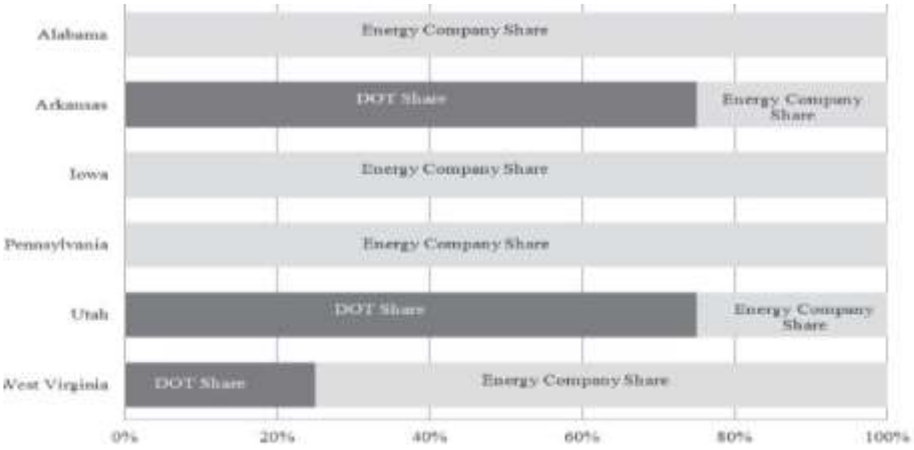


Figure 10
Level of rehabilitation cost sharing in different states [8]

Table 3 summarizes the strategies implemented by different states to recover the damage costs to infrastructures by energy-related activities. The application of pavement preservation treatments was reported to be very effective and the posting of load limits was reported to be effective to some extent.

Table 3
Strategies implemented in different states to recover the damage costs to infrastructures by energy-related activities [8]

State or Organization	Practice (s) Reported to recover the damage costs
Minnesota	State legislation allows for special hauling permits for heavy vehicles with added axles, enabling permits fees to be deposited into a special account at Minnesota DOT for use in bridge inspections and signage.
Missouri	Permit fees are applied to energy developers
Montana	Planning forecast studies identified high-use corridors for energy development to facilitate design modifications and accelerate reconstruction projects to satisfy forecast demands
New Jersey	The traffic data of overweight vehicles are collected and the damage will then be translated to cost over time, which will be used to influence the fee structure for overweight permit.
U.S. Forest Service	Road use permit for energy development activities requires energy developer pay for repair or reconstruction of roads directly or through donation of materials and/or equipment.
Three Affiliated Tribes (TAT)	Lump sum royalty pavements and maintenance agreements with energy companies; 5% gross value tax applied to oil produced from an American Indian Holding within the boundary of a reservation.
Texas	Texas Department of Motor Vehicles has developed standard permitting operation for OS/OW vehicles and the mechanism for charging fees is proposed to be based on actual vehicle weight with variations, such as different axle configurations. Some counties have maintenance agreements for rebuilding roadways with energy companies.
Pennsylvania	Pennsylvania DOT can post its roadways with a weight restriction and user must to obtain a permit to haul on the roadway. An excess maintenance agreement, security bond, and permit are all required from an energy development company to ensure that it repairs damages caused to infrastructure.
North Dakota	The state legislature imposes oil and gas gross production tax and an oil extraction tax in lieu of property taxes on oil and gas producing properties. Oil company pay a combined 11.5% in annual taxes on oil extraction and production since 2008.

OBJECTIVE

The objectives of this study included:

1. to quantify the pavement damage caused by the shale oil/gas development activities,
2. to estimate the damage costs and recommend a strategy of fiscal remedies

SCOPE

In this study, the impact of the shale gas development in the Haynesville area on Louisiana roadways was investigated by using the overweight permits data. The data of overweight trips in this area from 2006 to 2016 was extracted by RStudio and was assigned to the Louisiana roadway network with ArcGIS according to the shortest path method. The vehicle miles traveled (VMT) was calculated in terms of roadway classification, and the damage costs were estimated thereafter in network level based on the distribution of overweight trips on the Louisiana roadway network.

A matrix approach based on the shale gas well numbers was also developed to quantify the distribution of shale-gas related overweight truck trips on Louisiana roadways. DOTD identified 12 damaged roads in the shale gas area. The researchers compared the results from the Pavement Management System (PMS) database to the results of their own on the conditions with or without shale-gas related truck trips of these roads. Then pavement life-cycle cost analysis was conducted to calculate the damage cost due to shale gas truck traffic during energy development activities. The damage costs for different gross vehicle weight (GVW) were also studied. Then the obtained results were applied to recommend permit fee regulation for overweight trucks in Louisiana.

METHODOLOGY

Investigation Area in This Study

As indicated in Figure 11, most of the shale gas wells drilled in the past years are on the Haynesville shale play. Roadways in the seven parishes of this area, including Bienville, Bossier, Caddo, De Soto, Natchitoches, Red River, and Sabine, have been impacted by the shale gas development. The area of these parishes, hereafter referred to as the Haynesville area, is the investigation area of this study. In the Haynesville area, 3,241 horizontal wells in total were drilled in 2006 - 2016. In the first two years, however, there were less than 10 wells drilled. The drilling of most of shale gas wells began increasing in 2008, peaked in 2010, and dropped to a moderate level in 2012.

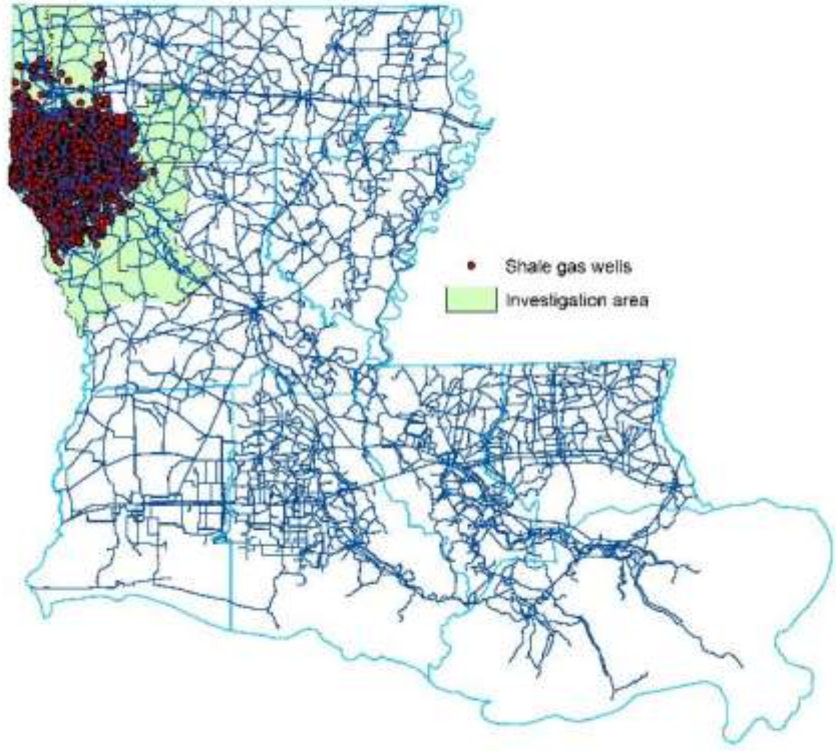


Figure 11
Investigation area

Data Sources

Oversize/Overweight Database

The Overweight/Oversize database provided by the permit office of Louisiana DOTD served as the data source of this study. The database was managed by SQLite studio (Figure 12).

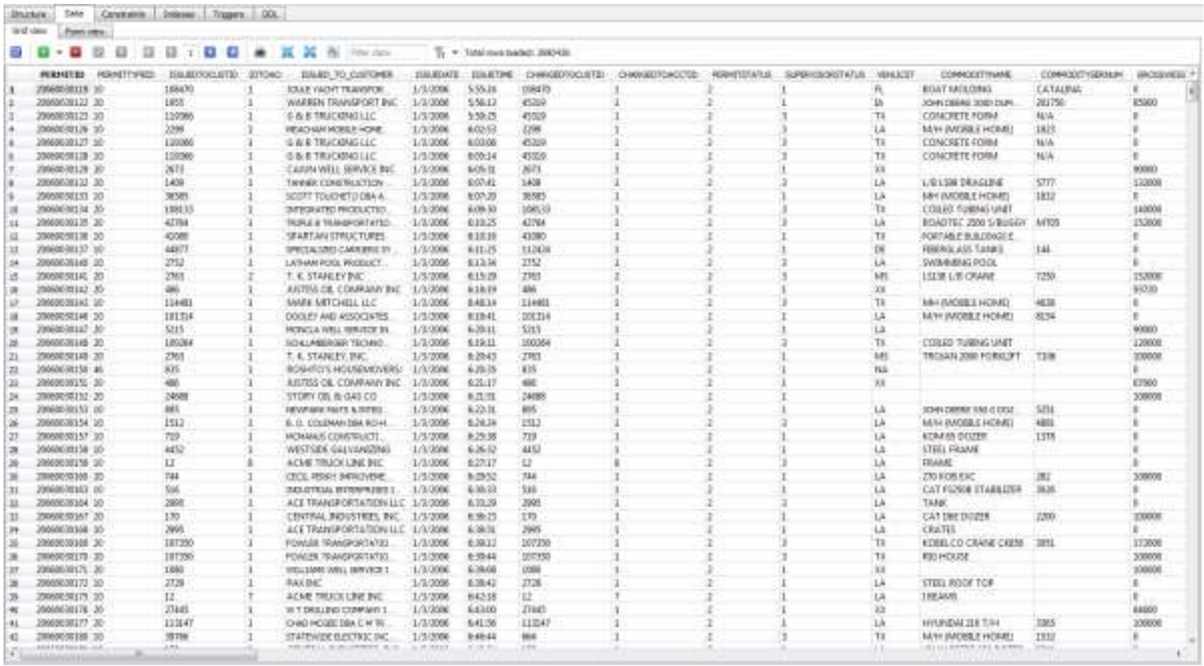
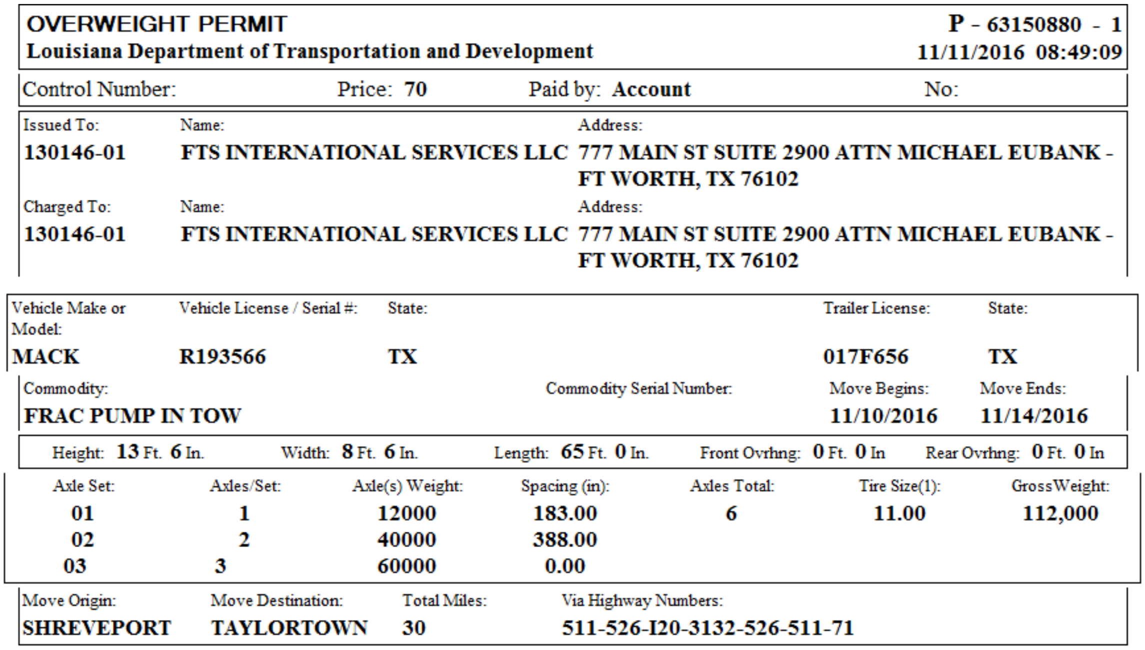


Figure 12
Database managed by SQLite Studio

In total, there were 2,690,426 permits issued by the permit office in 2006 - 2016. The typical entries on the permit include Permit ID, Permit type ID, Issue Date, Origin, Destination, Route String, Total Miles, Gross Weight, Axle Weight, Prices, etc., as shown in Figure 13. The permit types can be determined by permit type ID (see Figure 14), including Oversize, Overweight, Solid Waste, Harvest Season, etc. This study focused the impact of overweight truck trips in shale gas development areas on Louisiana roadways. Therefore, only the overweight permits were extracted. In total, the number of overweight permits extracted was 1,177,228 in 2006 - 2016. These overweight permits include the information of the overweight trips throughout the state. In most cases, one overweight permit represents one overweight trip.



OVERWEIGHT PERMIT **P - 63150880 - 1**
Louisiana Department of Transportation and Development **11/11/2016 08:49:09**

Control Number:	Price: **70**	Paid by: **Account**	No:

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Vehicle Make or Model:	Vehicle License / Serial #:	State:	Trailer License:	State:
MACK	**R193566**	**TX**	**017F656**	**TX**

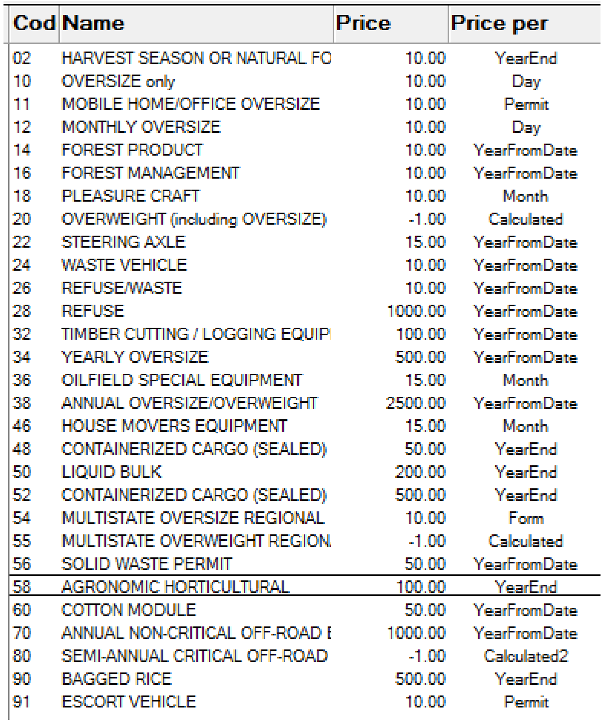
Commodity:	Commodity Serial Number:	Move Begins:	Move Ends:
FRAC PUMP IN TOW		**11/10/2016**	**11/14/2016**

Height: **13** Ft. **6** In.	Width: **8** Ft. **6** In.	Length: **65** Ft. **0** In.	Front Ovrhng: **0** Ft. **0** In	Rear Ovrhng: **0** Ft. **0** In

Axle Set:	Axles/Set:	Axle(s) Weight:	Spacing (in):	Axles Total:	Tire Size(1):	Gross Weight:
01	**1**	**12000**	**183.00**	**6**	**11.00**	**112,000**
02	**2**	**40000**	**388.00**			
03	**3**	**60000**	**0.00**			

Move Origin:	Move Destination:	Total Miles:	Via Highway Numbers:
SHREVEPORT	**TAYLORTOWN**	**30**	**511-526-I20-3132-526-511-71**

Figure 13
Primary entries of a typical overweight permit



Cod	Name	Price	Price per
02	HARVEST SEASON OR NATURAL FO	10.00	YearEnd
10	OVERSIZE only	10.00	Day
11	MOBILE HOME/OFFICE OVERSIZE	10.00	Permit
12	MONTHLY OVERSIZE	10.00	Day
14	FOREST PRODUCT	10.00	YearFromDate
16	FOREST MANAGEMENT	10.00	YearFromDate
18	PLEASURE CRAFT	10.00	Month
20	OVERWEIGHT (including OVERSIZE)	-1.00	Calculated
22	STEERING AXLE	15.00	YearFromDate
24	WASTE VEHICLE	10.00	YearFromDate
26	REFUSE/WASTE	10.00	YearFromDate
28	REFUSE	1000.00	YearFromDate
32	TIMBER CUTTING / LOGGING EQUIP	100.00	YearFromDate
34	YEARLY OVERSIZE	500.00	YearFromDate
36	OILFIELD SPECIAL EQUIPMENT	15.00	Month
38	ANNUAL OVERSIZE/OVERWEIGHT	2500.00	YearFromDate
46	HOUSE MOVERS EQUIPMENT	15.00	Month
48	CONTAINERIZED CARGO (SEALED)	50.00	YearEnd
50	LIQUID BULK	200.00	YearEnd
52	CONTAINERIZED CARGO (SEALED)	500.00	YearEnd
54	MULTISTATE OVERSIZE REGIONAL	10.00	Form
55	MULTISTATE OVERWEIGHT REGION	-1.00	Calculated
56	SOLID WASTE PERMIT	50.00	YearFromDate
58	AGRONOMIC HORTICULTURAL	100.00	YearEnd
60	COTTON MODULE	50.00	YearFromDate
70	ANNUAL NON-CRITICAL OFF-ROAD	1000.00	YearFromDate
80	SEMI-ANNUAL CRITICAL OFF-ROAD	-1.00	Calculated2
90	BAGGED RICE	500.00	YearEnd
91	ESCORT VEHICLE	10.00	Permit

Figure 14
Permit type included in the database

Shale Gas Wells

Information of shale gas wells in Haynesville shale play in 2006-2016 was extracted from the website of Department of Natural Resources (DNR), as shown in

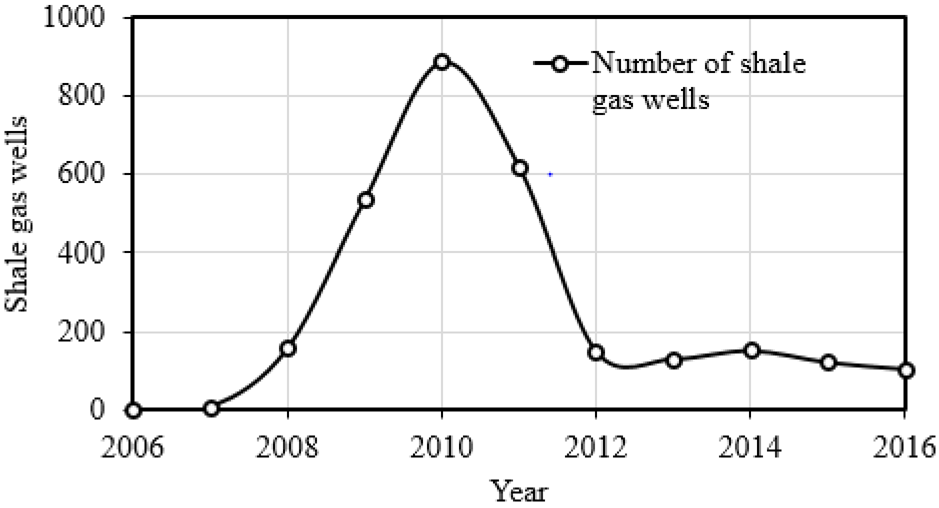


Figure 15.

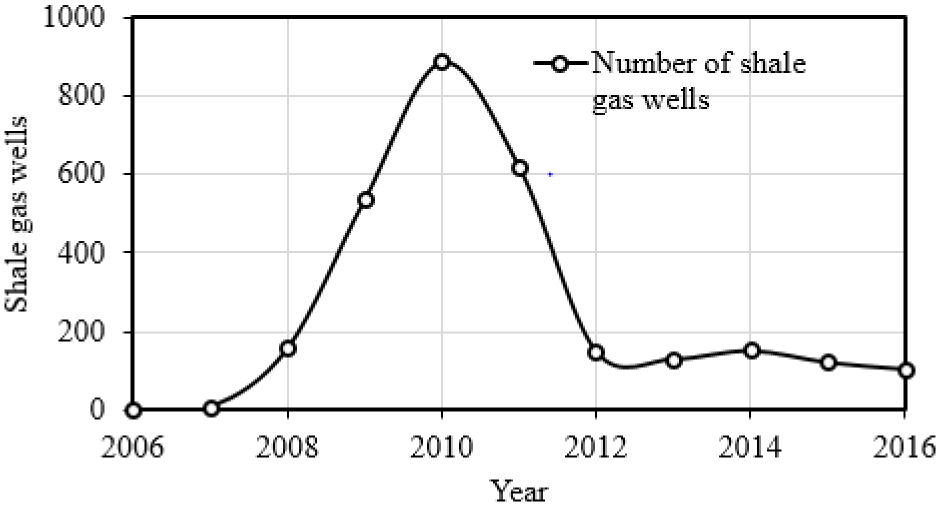


Figure 15
Number of shale gas wells in Haynesville area per year

Damaged Roadways

DOTD identified 26 roadways in the Haynesville area (Figure 16) impacted by the activities of shale gas recovery as damaged during the shale gas covering period, as listed in Table 4. The damaged roadways was also allocated on the Haynesville area.

Table 4
Identified damaged roadways

Route	**Control section**	**CS Length**	**Damaged Length**	**Cost Estimate (1,000 USD)**
US 171	02507	7.81	2.25	1237.5
La 5	04901	15.8	15.81	4347.75
La 1	05307	18.8	2	550
La 157	08201	2.21	2.24	616
La 154	09004	14.8	8.66	2381.5
La 169	09701	9.96	9.88	2717
La 5	09802	4.1	4.07	1119.25
La 5	09803	8.46	8.47	2329.25
La 5	09804	1.12	1.11	500
La 191	09903	5.99	6.02	1655.5
La 514	10001	9.84	1.98	816.75
La 3015	29802	8.83	8.81	2422.75
La 481	29902	10.9	4.63	2546.5
La 513	30004	14.8	8.32	2288
La 346	30030	2.87	2.83	1100
La 512	30102	7.59	7.56	2079
La 346	30103	6.88	6.89	1894.75
La 515	30202	5.61	1.75	481.25
La 783	30302	3.75	3.73	1025.75
La 783	30303	3.46	3.5	962.5
La 786	30602	5.13	5.14	1413.5
La 191	43202	8.34	8.4	2310
La 790	80701	3.81	3.83	2106.5
La 789	80907	6	6.15	1691.25
La 789	81609	2.67	2.7	742.5
La 788	84102	2.28	2.28	627

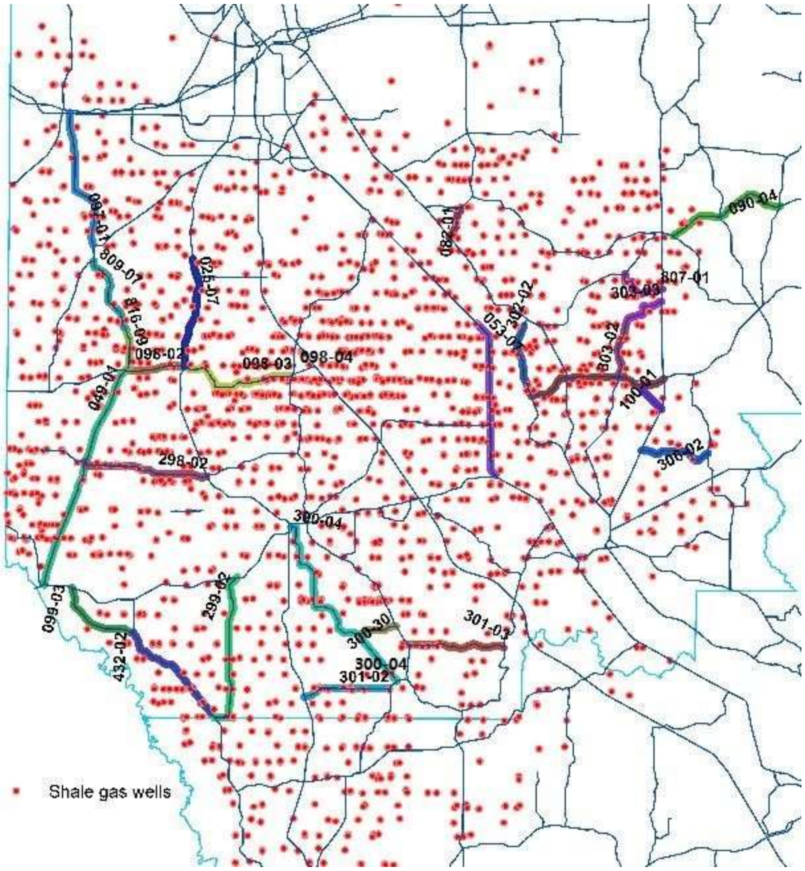


Figure 16
Locations of the damaged roadways in Haynesville area

Pavement Structures and Pavement Conditions

The pavement structures of the identified damaged roadways were retrieved from the Content Manager system maintained by DOTD. The pavement structures were categorized into three groups, new asphalt pavements (see Table 5), rigid/composite pavements (see Table 6), and overlay pavements (see Table 7). The ADT data were also extracted from the DOTD website, as shown in Appendix. The Historical Pavement condition data of the 26 roadways in the Haynesville area were retrieved from the Louisiana Pavement Management System.

Table 5
Pavement structures of new asphalt pavements

Route	Control section	Begin logmile	End logmile	Final Inspection	Pavement structures	Subgrade Resilient modulus (psi)	Back-calculated design ESALs
LA0157	082-01	0	2.252	10/28/1994	1.5" AC+1.5" AC+8.5" Base course	8797	200,000
LA0169	097-01	0	9.88	4/2/1998	1.5" AC+2" AC+10" Cement stabilized Base	10278	770,000
LA191	432-02	0	8.4	1/6/2005	1.5" AC+2" AC+12" Cement treated Base	9549	390,000
LA346	300-30	0	2.879	1/12/2012	1.5" AC+2" AC+12" Cement treated Base	9176	390,000
LA5	098-03	0	8.465	11/4/1994	1.5" AC+5.5"AC+8.5" Base	9176	7,800,000
LA512	301-02	0	6.01	11/18/1986	1.5" AC+1.5"AC+8.5" Base	9176	220,000
LA513	300-04	4.16	8.47	9/22/2003	1.5" AC+2" AC+12" Cement treated Base	9176	390,000
LA783	303-02	0	3.737	10/27/1995	1.5" AC+2" AC+8.5" Cement stabilized Base	10278	500,000
LA783	303-03	0	3.471	1/14/1999	1.5" AC+2" AC+12" Cement treated Base	9916	470,000
LA789	816-09	0	2.7	9/1/1981	1.5" AC +2" AC +8.5" Cement stabilized base	10278	500,000

Table 6
Pavement structures of rigid/composite pavements

Route	Control section	Begin logmile	End logmile	Final Inspection	Overlay structures	Existing Pavement structures	Mill	Subgrade reaction modulus (pci)	Back-calculated design ESALs
US0171	025-07	4.14	7.666	5/14/2009	1.5" AC+ 2" AC	3.5" AC +9" PCC+ 6" Base	0	430	13,500,000
LA0005	049-01	9.53	15.79	12/9/1998	2" AC	6" PCC +4.5" base	0	410	1,730,000
LA0005	049-01	0	2.11	2/9/1999	2" AC	3.5"AC+ 6" PCC +4.5" Base	2"	415	1,730,000
LA0001	053-07	8.04	13.5	9/23/2002	2" AC	8.5" AC+7" PCC+ 4.5" Base	2"	515	8,050,000
LA0005	098-02	0	4.104	12/12/1994	1.5" AC+ 2" AC	3.5" AC+7" PCC	1.5"	410	3,150,000

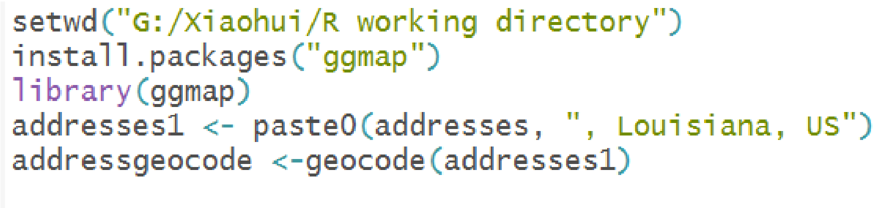
Table 7
Pavement structures of asphalt overlay pavements

Route	Control section	Begin_ logmile	End_ logmile	Final Inspection	Overlay structures	Existing Pavement structures	Mill	Subgrade resilient modulus (psi)	Back-calculated design ESALs
LA0154	090-04	0	8.66	2/12/1987	2" AC	3.5" AC +8.5" Cement stabilized base	1	9916	390,000
LA0191	099-03	0	5.995	8/30/2000	1.5" AC+2" AC	2" AC+8.5" Cement stabilized base	0	9176	1,050,000
LA0514	100-01	1	2.98	5/5/2009	1.5" AC	3" AC+ 8.5" Cement stabilized base	1	10278	163,000
LA3015	298-02	0	8.817	9/26/2001	2" AC	6" AC + 8.5" Cement stabilized base	0	9176	1,700,000
LA0481	299-02	0	4.62	1/14/1988	1.5" AC	3.5" +12" Base	1.5	9176	130,000
LA0512	301-02	6.01	7.56	2012	1.5" AC+1.5"AC	3.5" AC+8.5" Cement stabilized base	2	9176	500,000
LA0346	301-03	0	6.877	8/5/2010	1.5" AC+2" AC	3" AC+8.5" Cement stabilized base	1.5	9176	830,000
LA0515	302-02	0	5.099	4/7/1992	1.5" AC+2" AC	3" AC+8.5" Cement stabilized base	0	10278	2,150,000
LA0786	306-02	0	5.125	3/11/1988	1.5" AC	3.5" AC +8.5" Cement stabilized base	1.5	10278	163,000
LA0790	807-01	0	3.808	12/1/1965	3" AC	3" AC +8.5" Cement stabilized base	0	9916	265,000
LA0789	809-07	1.38	5.998	6/17/1985	1.5" AC +3.5" AC	3.5" AC +8.5" Cement stabilized base	2	10278	4,000,000
LA0788	841-02	0	2.28	11/13/1997	1.5+1.5	3" AC +8.5" Cement stabilized base	2	10278	290,000

Network-level Analysis

In this study, the impact of the shale-gas related overweight truck trips on Louisiana roadways was estimated by the following steps:

Step 1. Screen the Haynesville area related overweight permits using R language. As aforementioned, there were 1,177,228 overweight permits issued throughout the state in 2006 – 2016. To identify the overweight permits involved with the activities in the Haynesville area, a criterion that at least one end (either origin or destination) of an overweight trip is within the Haynesville area was applied for the extraction of the targeted overweight permits. Other permits that did not meet this criterion were excluded. RStudio, which is a software providing the working console for R language, was employed to gather the coordinates of the Origins/Destinations of the extracted overweight trips. Figure 17 shows typical codes used in R. Figure 18 illustrates the procedure of the data querying and the major R commands used in the process.



```
setwd("G:/Xiaohui/R working directory")
install.packages("ggmap")
library(ggmap)
addresses1 <- paste0(addresses, ", Louisiana, US")
addressgeocode <-geocode(addresses1)
```

Figure 17
Code used to fetch the GPS coordinates

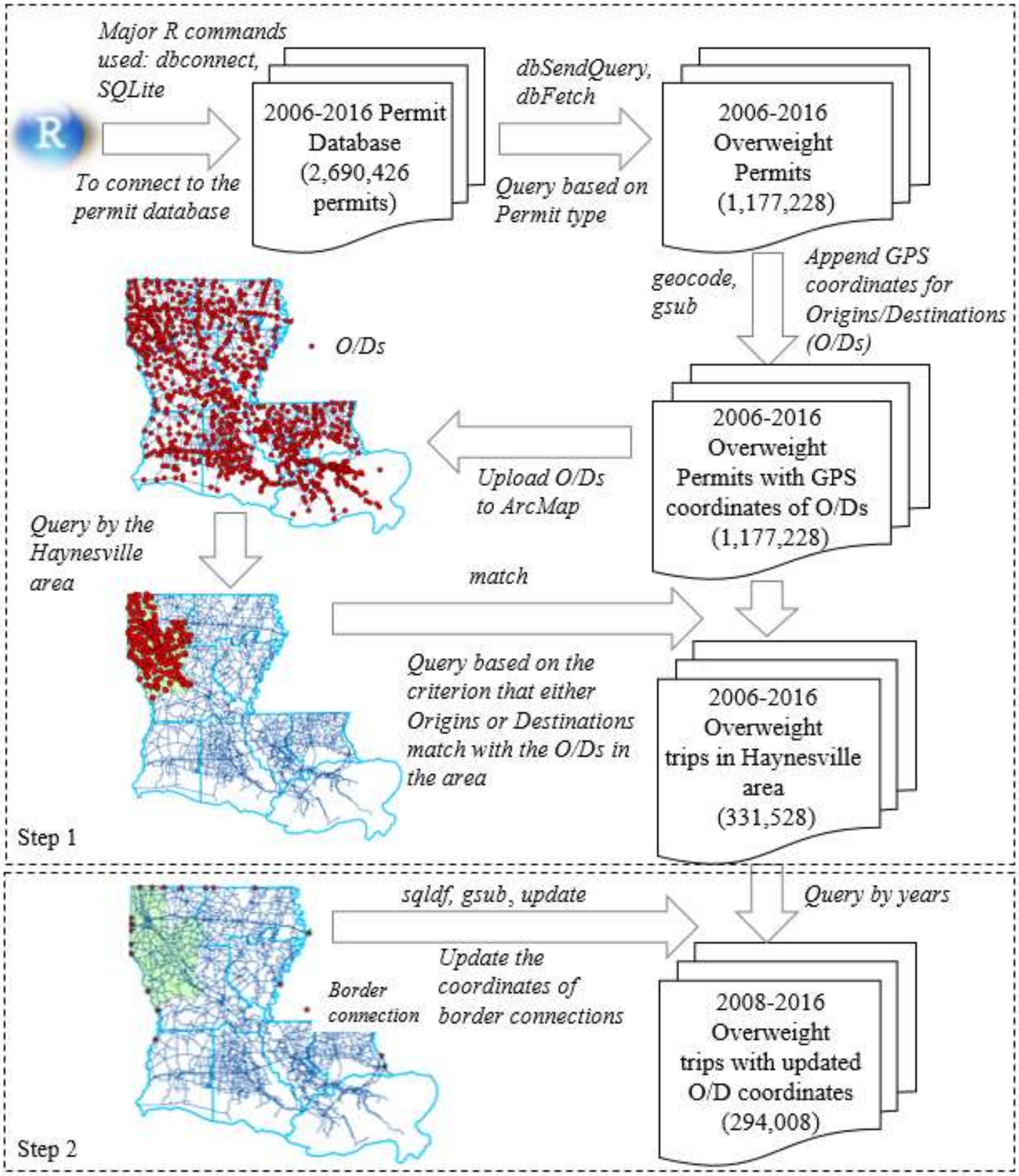


Figure 18
Flow chart of data processing in Step 1 and Step 2

Step 2. Preparation of the Origin/Destination pairs of the overweight trips. For those trips crossing borders (with one end to and from Texas, Mississippi, or Arkansas), the GPS coordinates were updated based on the beginnings or tails of route strings, as illustrated in Figure 2. The entry of Route Strings in the permit database contains the information of the cross-border routes (the heads or the tails of the router strings). The coordinates of the cross border routes were then gathered and served as the origins or destinations of the trips. For instance, for a cross-border trip from Texas to the Haynesville area with a Route String of "I20-LA169-LA789…", the geolocation of I20 intersecting with the Texas-Louisiana border was considered as the origin of the trip.

Step 3. Assign the overweight trips on the Louisiana roadway map according to the shortest path method. The overweight trips between the Origin-Destination pairs related to Haynesville area were assigned on the map of Louisiana roadways by the Network Analyst in ArcGIS according to the shortest path method.

Step 4. Calculate the vehicle miles traveled. With the analyzing results of Network Analysis, the occurrence frequencies of the roadway segments on the Louisiana roadway layer were counted by RStudio. Vehicle miles traveled (VMT) on a roadway segment was calculated by multiplying the frequencies of the roadway segment by its length. The total VMT throughout the state was calculated by summing the VMT of each roadway segment and also categorized in terms of the roadway classifications, including Interstate, US highway, Louisiana roadway (ADT>2000), and Louisiana roadway (ADT≤2000).

Step 5. Damage cost analysis. The damage cost was estimated based on the unit cost per ESAL consumption of each type of roadway classification. With the unit cost per ESAL per mile on each type of roadway and the overweight truck factor, the damage cost per overweight trip per mile was estimated. Subsequently, the damage cost of each type of roadway was quantified by multiplying the damage cost per overweight trip per mile with the corresponding total VMT of that roadway type.

Project-level Analysis

Estimation of Shale Gas Trips on the 26 Impacted Roadways

Trip Estimation Zones. According to the townships in the Public Land Survey System of Louisiana, the Haynesville area was divided into 15 truck trip estimation zones, as shown in Figure 19. The number of shale gas wells in each zone per year are shown in

Table 8. In Figure 19, the wells that are not covered by any zones were added into the adjacent zone.

Table 8
Shale gas wells in each zones

Zone	Shale gas wells											
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	No. of wells
1	0	0	10	5	16	18	1	4	3	0	0	57
2	3	8	22	55	26	7	1	2	2	0	6	132
3	0	0	19	42	62	39	27	39	15	9	3	255
4	0	0	30	38	72	60	33	31	56	40	0	360
5	0	0	2	24	73	47	3	2	4	1	1	157
6	0	0	28	43	85	41	9	0	6	16	24	252
7	0	0	11	90	194	148	56	16	41	15	31	602
8	0	0	17	67	101	62	16	57	38	16	21	395
9	0	0	11	46	63	40	6	19	4	12	18	219
10	0	0	5	35	40	23	1	1	1	11	14	131
11	0	0	10	55	43	29	4	0	0	1	4	146
12	0	0	0	22	65	38	3	1	8	7	7	151
13	0	0	1	9	41	29	11	2	0	3	2	98
14	0	0	2	24	42	61	37	3	2	4	0	175
15	0	0	1	10	41	48	4	0	5	2	0	111
Total	3	8	169	565	964	690	212	177	185	137	131	3241

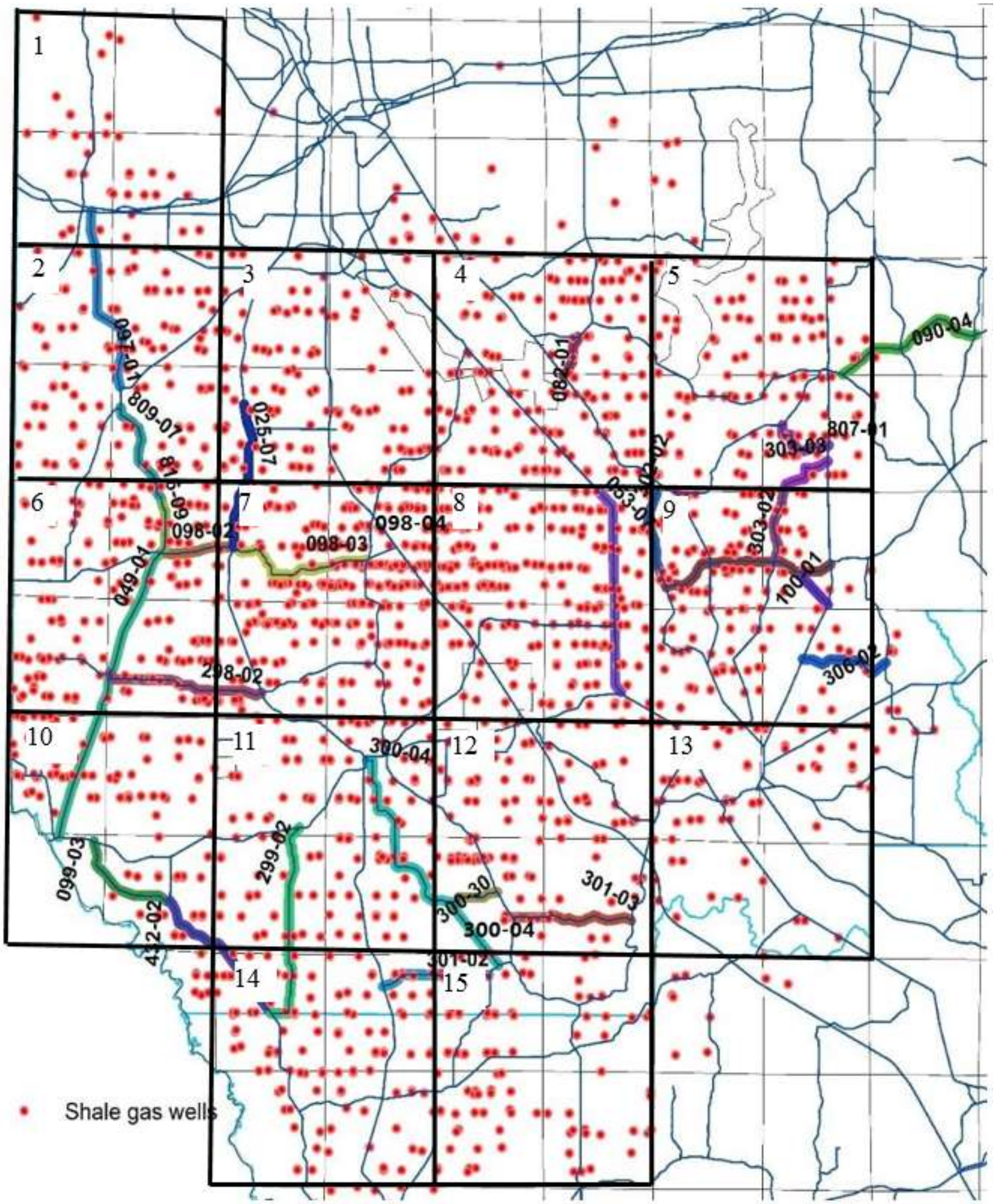


Figure 19
Trip estimation zones

Trip Generation. Table 9 summarizes the total one-way trips generated per well according to previous studies. The table includes two scenarios: one is that all water is transported by truck and the other is that water is primarily transported by pipelines. In this study, fresh water is transported by the pipelines and the salt-water is hauled by trucks to injection wells. Therefore, modification was conducted for this study and it was estimated that 648 truck trips are needed per shale gas well. For scenarios with multiple wells per pad, the estimated truck trips per well was estimated and summarized in Table 10.

Table 9
Truck trips required per well [18]

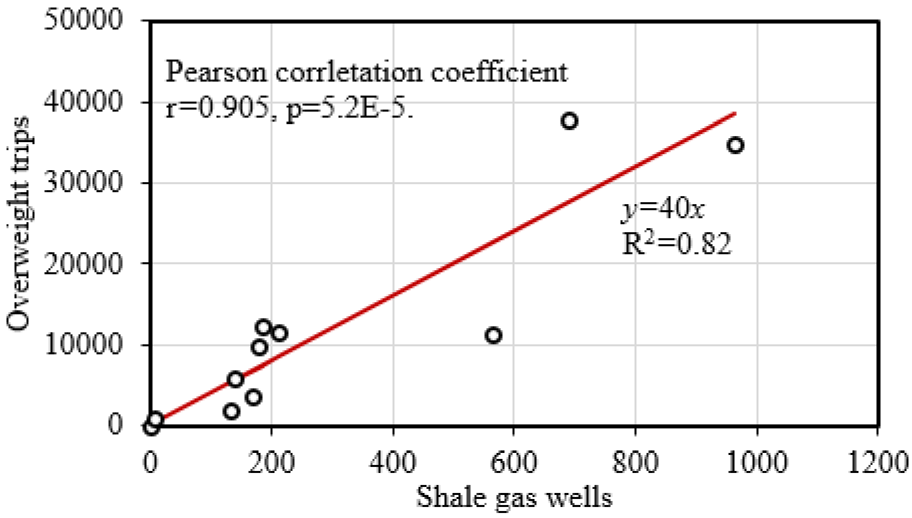
Well pad activity	Number of heavy truck trips for a single well	
	All water transported by truck	Pipelines may be used for water transportation
Pad and Road Construction	45	45
Rig mobilization	95	95
Drilling Fluid [a]	45	45
Drilling Equipment	45	45
Drilling (rig crew, etc.)	50	50
Completion Fluid and Materials	20	20
Completion Equipment (pipe, wellhead etc.)	5	5
Fracture Equipment (pump trucks, tanks etc.)	175	175
Hydraulic fracturing water hauling	500	60 (0)[b]
Fracture Sand	23	23
Produced water disposal	100	17 (100)
Final pad prep	45	45
Total one-way, Loaded trip per well	1148	625 (648)

[a] Shaded items mean that truck trips cannot share with other wells in the same pad.
[b] The number in parentheses is the modified data for this study.

Table 10
Truck trips required per well in different scenarios

Wells per pad	Truck trips per well	Overweight truck trips per well
4	341	40 [a]
6	306	
8	289	

[a] Estimated based on



(b)

Figure 24.

Matrix of Interaction Factors. The trip estimation zones interact with each other due to the interconnection by roadways. To conduct a traffic flow analysis, origins and destinations of trips are required. The locations of the shale gas wells can serve as one of the origins/destinations; however, the other ends of the trips are unknown. Previous studies adopted projected locations as the other ends, but the projection is uncertain and arguable. This study attempted to assign the trips based on the possibility of traffic in the roadway network. With the assumption that the possibility of each roadway used by traffic flow is identical, the interaction factor can be determined thereafter.

For Zone $\boldsymbol{i}$ and Zone $\boldsymbol{j}$, which are adjacent to each other,

$$\boldsymbol{f_{ij}} = \frac{\boldsymbol{N_{ij}}}{\boldsymbol{N_i}} \tag{1}$$

$$\boldsymbol{t_{ij}} = \frac{\boldsymbol{N_{ij}}}{(\boldsymbol{N_i}-\boldsymbol{1})} \tag{2}$$

where $\boldsymbol{f_{ij}}$ is the interaction factor of Zone $\boldsymbol{i}$ to Zone $\boldsymbol{j}$;

$\boldsymbol{t_{ij}}$ is the transfer factor of Zone $\boldsymbol{i}$ to Zone $\boldsymbol{j}$;

$\boldsymbol{N_{ij}}$ is the number of roadway connections between Zone $\boldsymbol{i}$ and Zone $\boldsymbol{j}$;

$\boldsymbol{N_i}$ is the number of outlets of Zone $\boldsymbol{i}$.

For Zone $\boldsymbol{i}$ and Zone $\boldsymbol{j}$, both of which are adjacent to Zone $\boldsymbol{k}$ but not adjacent to each other,

$$\boldsymbol{f_{ij} = \frac{N_{ik}}{N_i}\frac{N_{kj}}{(N_k-1)} = f_{ik}t_{kj}} \quad (3)$$

where $\boldsymbol{f_{ij}}$ is the interaction factor Zone $\boldsymbol{i}$ to Zone $\boldsymbol{j}$;

$\boldsymbol{N_{ik}}$ is the number of roadway connections between Zone $\boldsymbol{i}$ and Zone $\boldsymbol{k}$;

$\boldsymbol{N_i}$ is the number of outlets of Zone $\boldsymbol{i}$.

Similarly, for Zone $\boldsymbol{i}$ and Zone $\boldsymbol{j}$ interacting with each other through the intermediary zones of Zone $\boldsymbol{k}$, Zone $\boldsymbol{l}$, Zone $\boldsymbol{m}$, and Zone $\boldsymbol{n}$, the interaction factor can be written as:

$$\boldsymbol{f_{ij} = f_{ik}t_{kl}t_{lm}t_{mn}t_{nj}} \quad (4)$$

When the number of intermediary zones are more than four, the interaction factor is negligible.

Number of Truck Trips in Each Zone. The truck trips related to shale gas recovery activities in each zone can be estimated by

$$\boldsymbol{Total\ trip_i = \sum_{j=1}^{15} Trip_j f_{ij}} \quad (5)$$

where $Total\ trip_i$ is the total trips in Zone i;

$Trip_j$ is the number of trips in Zone j generated by shale gas wells in Zone j, $Trip_j$ can be estimated by $Well_jT$, in which $Well_j$ is the number of wells in Zone j and T is the number of trips required by a single well (e.g., 648 or 341).

Number of Truck Trips on Impacted Roadways. Considering that each route has one inlet and one outlet in the trip estimation zone, the number of routes can be estimated by the following equation accordingly.

$$\boldsymbol{R_i = \frac{N_i}{2}} \quad (6)$$

where $\boldsymbol{R_i}$ is the number of routes in Zone i.

Assuming that the truck trips can be evenly assigned on the routes in each zone, the number of truck trips on impacted roadways in each zone can be expressed as

$$\boldsymbol{Trips\ on\ impacted\ roadways} = \frac{\boldsymbol{Total\ trip_i}}{\boldsymbol{R_i}} \qquad (7)$$

Pavement Analysis and Damage Cost Estimation

Two scenarios of traffic inputs were taken into consideration: original ADT without shale gas traffic and original ADT with shale gas traffic. Both the AASHTO 1993 design method and the Pavement ME design method are proposed to conduct the analysis. The obtained results from the two methods will be compared with each other for validation purpose.

Method Based on AASHTO 1993 Design Guide. For the AASHTO 1993 method, the following design data in the DOTD database will be needed:

- Ordinary ESALs based on ADT results in the pavement service life
- Extra ESALs due to shale gas recovery
- Pavement condition index in the PMS database

According to the Pavement condition index in the PMS database, the construction cost for repairing a roadway impacted by shale-gas related overweight trucks can be estimated in terms of various repairing strategies. The damage cost due to the shale-gas related overweight trucks can be estimated as:

$$\boldsymbol{Damage\ cost} = \frac{\boldsymbol{Extra\ ESALs\ due\ to\ shale\ gas\ recovery}}{\boldsymbol{Total\ ESALs\ applied}} \times \boldsymbol{Cost} \qquad (8)$$

Method Based on Pavement ME. For the Pavement ME design method, the following design data in the DOTD database will be retrieved for the analysis of the damaged roads.

- Year of construction (overlay)
- Average Annual Daily Truck Traffic (AADTT)
- Growth factor
- Vehicle classification distribution
- Structural properties (Layer thickness)
- Material properties
- Climate condition

Traffic Inputs. The overloaded truck trips in the Haynesville area was analyzed based on Oversize/Overweight database. The trucks were categorized into four types, class 6, class 10, class 12 and class 13. Table 11 summarizes the vehicle class distribution and axle per truck.

Table 11
Vehicle class distribution and axles per truck for overweight trucks

Truck type	Distribution (%)	Single	Tandem	Tridem	Quad*
Class 6	10.24	0.18	1.11	0.71	0.04
Class 10	84.21	1	0.78	0.79	0.45
Class 12	4.29	1.96	1.05	0.72	0.29
Class 13	1.27	1.31	1.70	1.74	0.16

*Combined with Five-axle.

In the pavement analysis, the traffic will be input as two categories, with and without overweight truck trips. For the traffic input without overweight truck trips, the AADTT and vehicle class distribution will be input by following Louisiana's input guideline. The vehicle class distribution and axles per truck for the legal traffic in Louisiana was shown in Table 12. Considering the traffic volume of the studied area, the Louisiana Truck Traffic Classification Group 1 (TTC 1) was adopted as load spectrum for local traffic without shale-gas related overweight truck. The details of TTC Group 1 load spectrum can be found in Appendix D.

Table 12
Vehicle class distribution and axles per truck for legal trucks

Truck type	Distribution (%)	Single	Tandem	Tridem	Quad*
Class 4	4.98	1.62	0.39	0	0
Class 5	36.85	2	0	0	0
Class 6	13.98	1.02	0.99	0	0
Class 7	1.42	1	0.26	0.83	0
Class 8	13.27	2.38	0.67	0	0
Class 9	25.12	1.13	1.93	0	0
Class 10	2.73	1.19	1.09	0.89	0
Class 11	0	0	0	0	0
Class 12	0	0	0	0	0
Class 13	1.65	2.15	2.13	0.35	0

*Combined with Five-axle.

For the traffic input with overweight truck trips, Table 11 and Table 12 are combined together to consider both the influence of the legal traffic and the overweight truck trips. Table 13 lists the values determined based on the assumption that the AADTT of the overweight truck trips is 400 and that of the legal truck trips is 1000. The load spectrums will also be combined together and import into the Pavement ME as XML files. Below listed the equations used for the combination.

Combined AADTT:

$$\text{AADTT}_c = \text{AADTT}_o + \text{AADTT}_l \tag{9}$$

where, AADTT_c is the combined AADTT;
AADTT_o is the AADTT of the overweight truck trips;
AADTT_l is the AADTT of the legal truck trips.

Combined vehicle class distribution of a certain truck type:

$$\text{Distribution}_c = \frac{\text{AADTT}_o \times \text{Distribution}_o + \text{AADTT}_l \times \text{Distribution}_l}{\text{AADTT}_c} \tag{10}$$

where, Distribution_c is the combined vehicle class distribution;
$\text{Distribution}_o$is the vehicle class distribution of the overweight truck trips;
Distribution_l is the vehicle class distribution of the legal truck trips.

Combined axle per truck (axle type can be one of the four types, including single axle, tandem, tridem, and quad) of a certain truck type:

$$\text{Axle}_c = \frac{\text{AADTT}_o \times \text{Distribution}_o \times \text{Axle}_o + \text{AADTT}_l \times \text{Distribution}_l \times \text{Axle}_l}{\text{AADTT}_c \times \text{Distribution}_c} \tag{11}$$

where, Axle_c is the combined axle per truck of a certain truck type;
$\text{Axle}_o$is the axle per truck of the overweight truck trips;
Axle_l is the axle per truck of the legal truck trips.

Combined load spectrum of an axle type, which can be one of the four types, of a certain truck type:

$$\text{spectrum}_c = \frac{\text{AADTT}_o \times \text{Distribution}_o \times \text{Axle}_o \times \text{spectrum}_o + \text{AADTT}_l \times \text{Distribution}_l \times \text{Axle}_l \times \text{spectrum}_l}{\text{AADTT}_c \times \text{Distribution}_c \times \text{Axle}_c}$$

(12)

where, $\text{spectrum}_c$is the combined load spectrum of one axle type of a certain truck type;
$\text{spectrum}_o$is the load spectrum of one axle type of the overweight truck trips;
spectrum_l is load spectrum of one axle type of the legal truck trips.

Table 13
Combined vehicle class distribution and axles per truck

Truck type	Distribution (%)	Single	Tandem	Tridem	Quad*
Class 4	3.56	1.62	0.39	0.00	0.00
Class 5	26.32	2.00	0.00	0.00	0.00
Class 6	12.91	0.83	1.02	0.16	0.01
Class 7	1.01	1.00	0.26	0.83	0.00
Class 8	9.48	2.38	0.67	0.00	0.00
Class 9	17.94	1.13	1.93	0.00	0.00
Class 10	26.01	1.01	0.80	0.80	0.41
Class 11	0.00	0.00	0.00	0.00	0.00
Class 12	1.23	1.96	1.05	0.72	0.29
Class 13	1.54	1.95	2.03	0.68	0.04

*Combined with Five-axle.

Material Inputs. The material and pavement structure data will be input according to the historical design data and the Louisiana default values listed in Table 14.

Table 14
Material inputs suggested for typical AC mixtures in Louisiana

Design Input	Superpave	Superpave	Superpave	Conventional	Conventional
Asphalt Binder	PG 76-22	PG 70-22	PG 64-22	PAC-40	PAC-30, AC-30
Use(WC=wearing course, BC=binder course, BS=base course)	Level 2 WC Level2 BC	Level 1 WC Level 1 BC	Level 1 BS	Type 8 WC Type 8 BC	Type 5 BS
Cumulative % passing 3/4 inch sieve	95	96	89	95	89
Cumulative % passing 3/8 inch sieve	69	72	72	70	74
Cumulative % passing #4 sieve	48	52	54	51	56

Design Input	Superpave	Superpave	Superpave	Conventional	Conventional
% passing #200 sieve	5.1	5.6	5.3	5.2	5.5
Effective binder content (%)	9.49	9.46	9.17	10.04	9.42
In-place air voids (%)	6.95	6.90	6.94	6.92	6.86
Total unit weight (pcf)	144	144	144	144	144

The pavement analysis will be done with two groups of traffic volumes as aforementioned, (a) design traffic and (b) design traffic and extra traffic generated from the shale oil/gas development activities. The difference of the distresses caused by the two groups of traffic volumes is the distress caused by the shale oil/gas development activities. Figure 20 shows the concept of the analysis of the reduction of the serviceable life due to the shale oil/gas development according to the control distress.

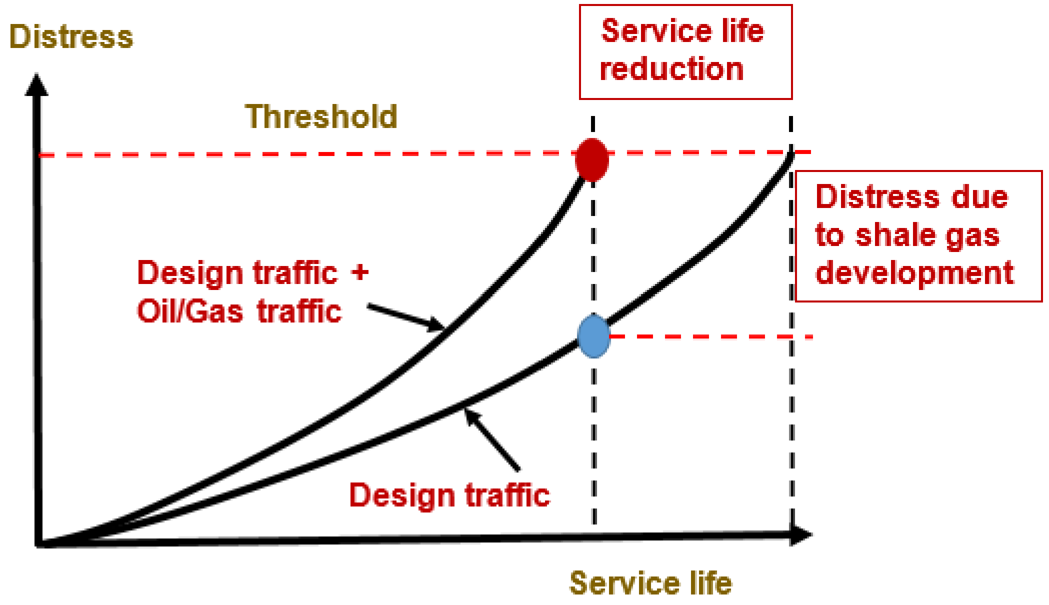


Figure 20
Service life reduction due to the impose of shale gas traffic

To specifically quantify the damage caused by the different gross weight range of overloaded truck, typical truck weight and axle configuration in the Pavement ME software will also be employed. The distresses due to different axle configuration can be compared by the number of truck trips for same damage level reached.

*Damage Cost Estimation***.** Equivalent Uniform Annual Cost (EUAC) is

$$\text{EUAC} = \text{Cost} \times \left(\frac{\text{A}}{\text{P}}, k, \text{n}\right) \tag{13}$$

where capital recovery can be expressed as

$$\left(\frac{\text{A}}{\text{P}}, k, \text{n}\right) = \frac{k(1+k)^n}{(1+k)^n-1} \tag{14}$$

k is the interest rate;
n is the pavement serviceable life, year.

For the two scenarios with and without shale-gas related overweight truck trips, the serviceable lives are n_1 and n_2, respectively. The distresses selected include IRI, Rutting, Fatigue cracking, longitudinal cracking, etc. The corresponding damage cost can be estimated as

$$\text{Damage cost per trips} = \text{Cost} \times \left[\left(\frac{\text{A}}{\text{P}}, k, n_1\right) - \left(\frac{\text{A}}{\text{P}}, k, n_2\right)\right]\frac{n_1}{N} \tag{15}$$

where, N can be the total number of shale-gas related overweight trips imposed on a specific roadway.

Historical Pavement Condition Data Retrieved from the PMS Database and Pavement Condition Survey

The analyzed pavement distresses will be validated by the PMS data and field evaluation (FWD test, cracking survey, etc.) will be conducted to evaluate the pavement condition.

DISCUSSION OF RESULTS

Network-level Analysis

Origins/Destinations within the Haynesville Area

Utilizing RStudio, it was found out that the 1,177,228 overweight permits include 6,160 unique origins/destinations in total and the frequencies of the 6,160 origins/destinations vary significantly. The permits with origins/destinations included in the first 1,000 with the highest frequencies account for 99.6% of the total overweight permits. The occurrences of other origins/destinations, mainly caused by misspelling or other human errors, are rare and therefore were neglected in the analysis. The geolocations of the 1,000 origins/destinations in Louisiana were then collected with the help of the RStudio. The function named *geocode* in the *ggmap* package of the RStudio was employed to gather the coordinates of these Origins/Destinations and the results are presented in ArcMap, as shown in Figure 21. The Origins/Destinations in the Haynesville area were then selected. To avoid missing any geolocations within the Haynesville area, all cities, towns, villages, communities, and census-designated areas in the seven parishes gathered from Smith [19] were used for verification. In total, there are 164 Origins/Destinations selected in the Haynesville area.

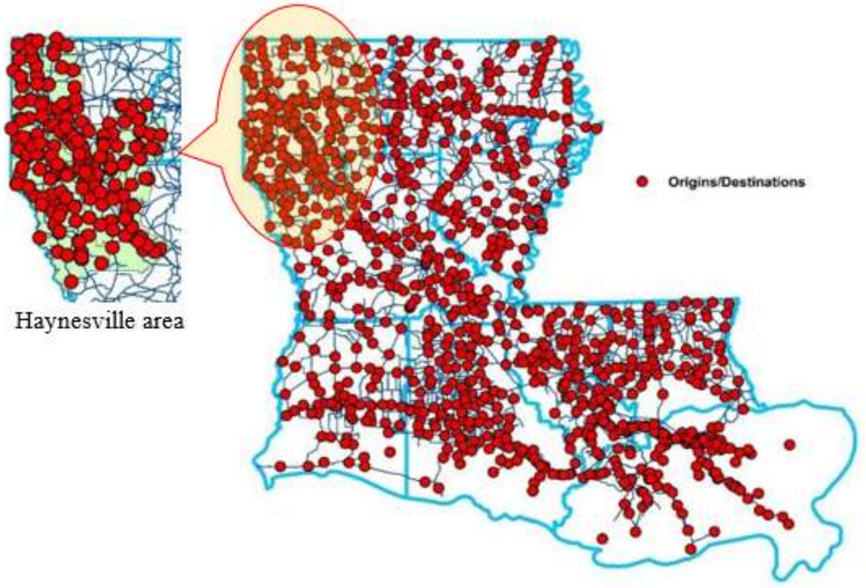


Figure 21
Geolocations of the Origins/Destinations in the Haynesville area

Screen of Overweight Trips Related to the Haynesville Area

In the 1,177,228 overweight permits across the state, those with either an Origin or a Destination matching with the selected Origins/Destinations in the Haynesville area were screened by using query language in the RStudio. In total, 315,746 permits in 2006 to 2016 satisfying the criterion were extracted. The number of corresponding overweight trips were 331,528 related to the Haynesville area in 2006 to 2016. The number of the overweight trips was higher than that of the overweight permits since some overweight permits contain multiple trips. Figure 22 and Figure 23 present the distributions of the gross weights and travel distances of the overweight truck trips.

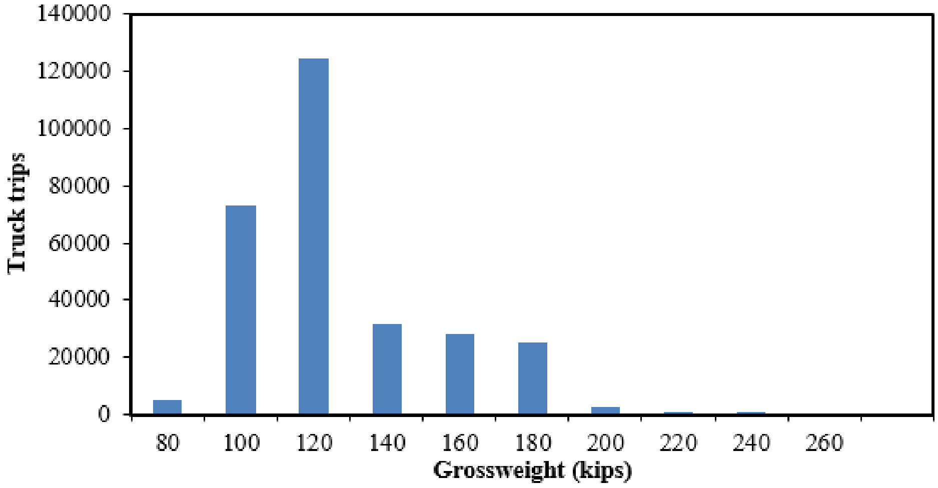


Figure 22
Gross weight of the overweight truck trips

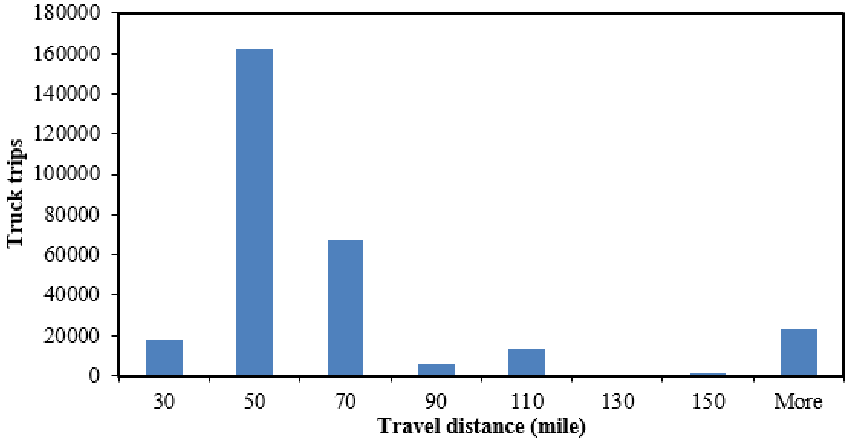
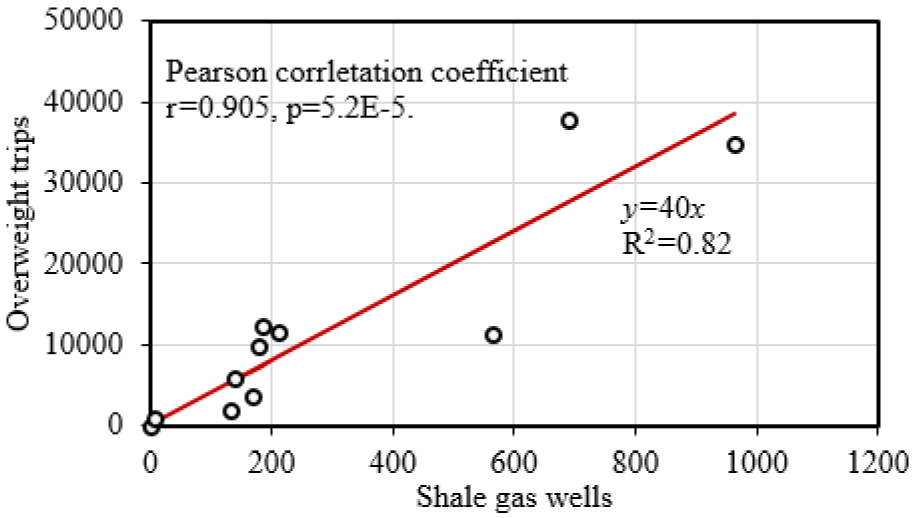
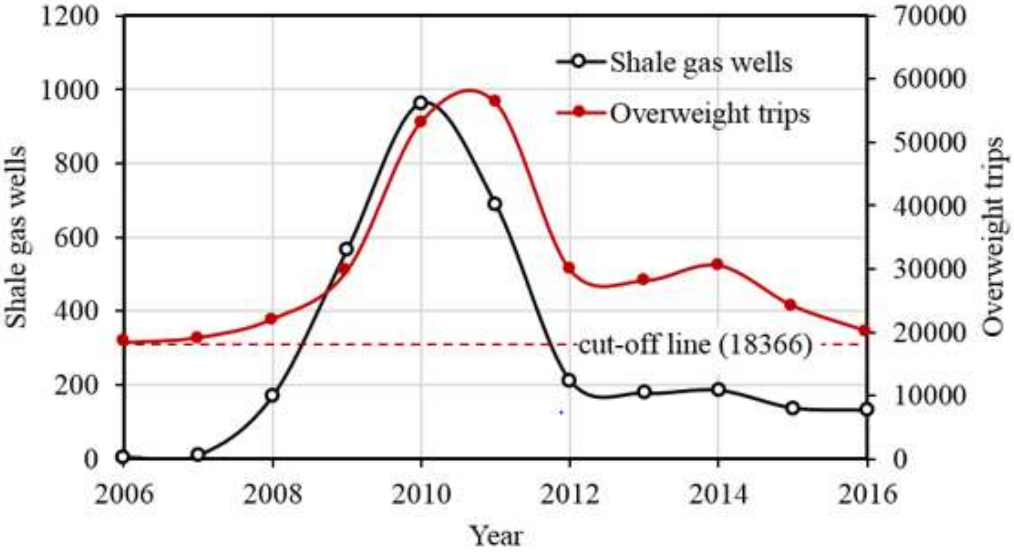


Figure 23
Travel distances of overweight truck trips

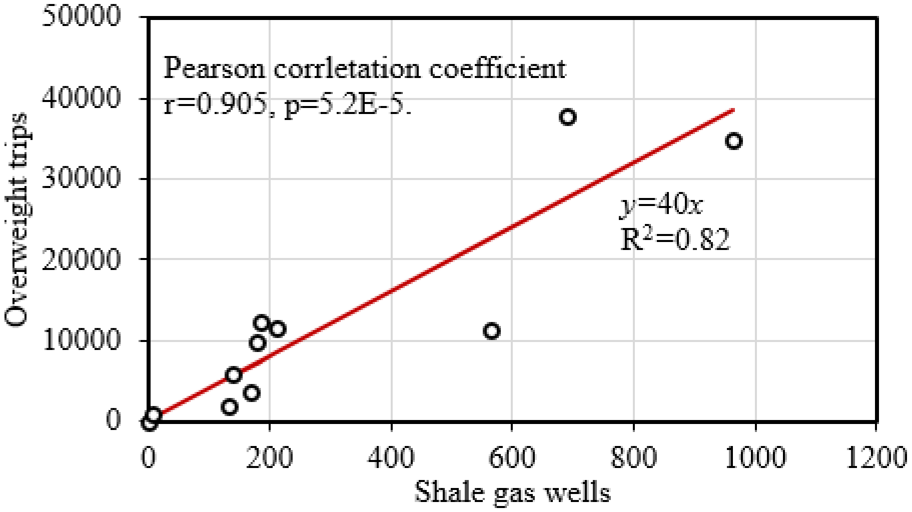


(b)

Figure 24 shows the comparison of the overweight trips and the number of shale gas wells spudded in the Haynesville area. As shown in the figure, the trend of the number of overweight trips per year was in a reasonable agreement with the number of shale gas wells spudded. This result indicates that the extraction of the overweight trips in this study were reasonable and acceptable. Clearly, most of the overweight trips in 2006 and 2007 (18,366 overweight trips in 2006) were not generated by the shale gas development since there were very few wells drilled in that period. Assuming that 18,366 overweight trips in each year (as the cut-off line in Figure 3 shows) were not related to the activities of the shale gas development, thus, the total shale gas-related overweight trips were estimated to be 129,502 by subtracting the non-related trips from the total. The percentages of the shale-gas related overweight trips in each year are shown in Table 15. On average, 39% {129,502/331,528} of the overweight trips in the Haynesville area are shale-gas related, and based on the correlation between shale gas well and overweight truck trips, it is concluded that 40 {129,502/3,241} overweight trips were generated during the construction of a single shale gas well.



(a)



(b)

Figure 24
Comparison of overweight trips and shale gas wells in the Haynesville area

Table 15
Percentages of the shale-gas related overweight trips in each year

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
percentage	0.0	4.1	16.8	38.1	65.5	67.3	38.5	34.6	39.9	24.0	8.9

Non-Overweight Trips Related to the Shale Gas Development

Although the main objective of this study was to estimate the impact of the shale-gas related overweight truck trips, an estimation of the impact of the associated non-overweight truck trips was also provided. In addition to the overweight trips, the drilling and completion of the shale gas wells also require a large number of legal heavy truck trips. New York State Department of Environmental Conservation [20] estimated that the total heavy truck trips used for the construction and operation of a single well range from 565 (without the hauling of hydraulic fracturing water) to 1,148. Interviewing the staff of the Louisiana Department of Natural Resources indicated that pipelines were mostly used for the transportation of the hydraulic fracturing water in the Haynesville area. Therefore, the total heavy truck trips (including the overweight and non-overweight trips) per well were chosen as 565 in this study, including 40 overweight trips and 525 {565-40} non-overweight trips. It should be pointed out that there are many non-overweight trips sharing the same route of an overweight trip during the construction of a shale gas well. Therefore, in this study, it was assumed that the non-overweight trips share the same routes of the overweight trips and one overweight trip is associated with 13 {525/40} non-overweight trips. Under this assumption, the non-overweight trips related to the shale gas development are 1,683,526 in 2006 - 2016.

Allocation of the Origins/Destinations of the Overweight Trips on an ArcMap

Even through the number of the shale-gas related overweight trips was estimated (i.e., 129,502), it was difficult to differentiate the shale-gas related overweight trips from the 331,528 overweight trips related to the Haynesville area. In this section, all the overweight trips related to the Haynesville area in 2008 - 2016 were allocated on the ArcMap. As discussed earlier, the overweight trips in 2006 and 2007 might not be shale-gas related and therefore were excluded from the analyses. In 2008 to 2016, there are 294,008 trips with either an origin or destination within the Haynesville area. In these trips, nearly half of them have both the origins and destinations in Louisiana and the rest are cross-border trips to and from Texas, Arkansas, and Mississippi. Thus, the origin-destination pairs of the overweight trips were divided into four categories, including:

- Arkansas-Haynesville (16,418 trips)
- Mississippi-Haynesville (16,190 trips)
- Texas-Haynesville (114,571 trips), and
- Louisiana-Haynesville (146,829 trips)

In these categories, both the two ends (origin and destination) of the Louisiana-Haynesville trips can be found in Figure 21. For the trip in the rest categories, only one end (origin or destination) of the trip can be found the figure and the other is labeled as Texas, Arkansas, or Mississippi. Therefore, the border connections, which serve as origins or destinations, have to be identified for the cross-border trips.

In the overweight permit database, the entry of Route Strings contains the information of the cross-border routes (the heads or the tails of the router strings). For a specific cross-border trip, based on the Route String, the route that crosses the border can be identified. The coordinate of the border connection can be then obtained and serve as the origin or destination of the trip. For instance, for a cross-border trip from Texas to Haynesville with a Route String of ‘I20-LA169-LA789…’, the geolocation of the intersection of I20 and the border was considered as the origin of the trip. For all the cross-border trips, the locations of border connections with high frequencies in the database as shown in Figure 25 to Figure 28 were assigned as origins or destinations and these border connections covered 99.2% of the cross-border trips. Other cross-border trips with a border connection were reassigned to the most common border connections in the corresponding category.

With the geolocations of the Origins/Destinations of all the 294,008 overweight trips, all the overweight trips with the coordinates of Origins/Destinations as well as the permit information were written in a CSV file.

Trip Assignment

The 294,008 Origin/Destination pairs included in the CSV file were uploaded in the Network Analyst of ArcGIS and solved the routes according to the shortest path method. With the analysis results and the help of RStudio, the overweight trips associated with the Haynesville area were distributed on the Louisiana roadway network, as shown in Figure 25 to Figure 29.

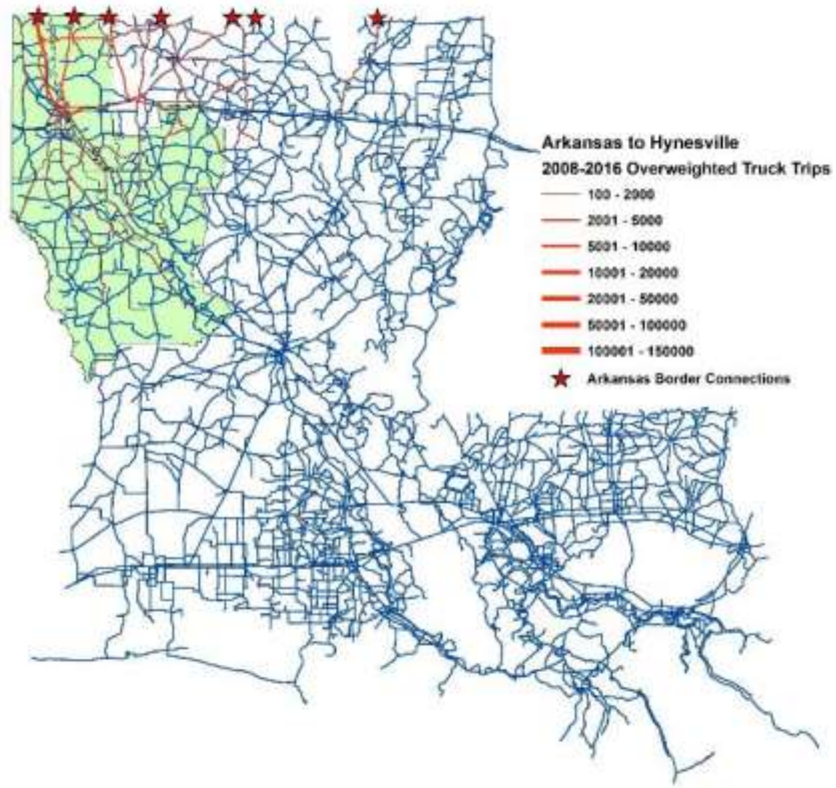


Figure 25
Trips from Arkansas to the Haynesville area

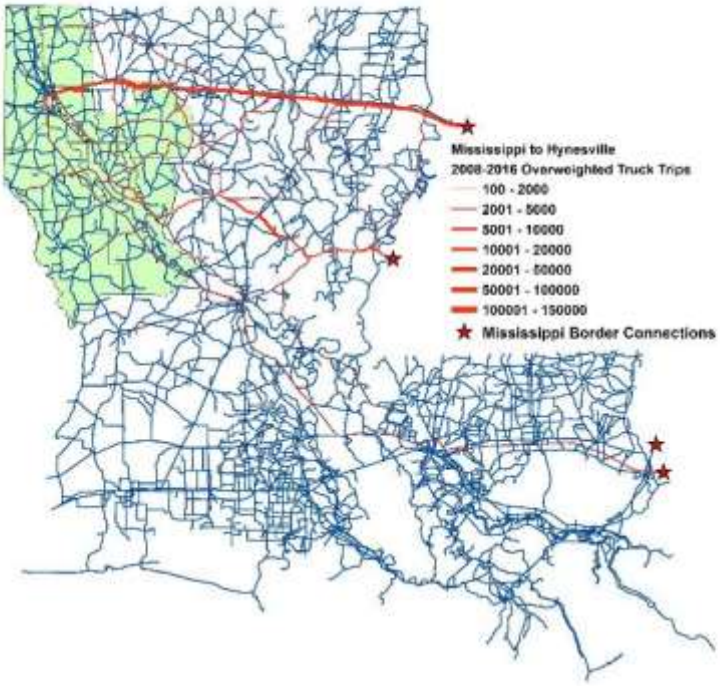


Figure 26
Trips from Mississippi to the Haynesville area

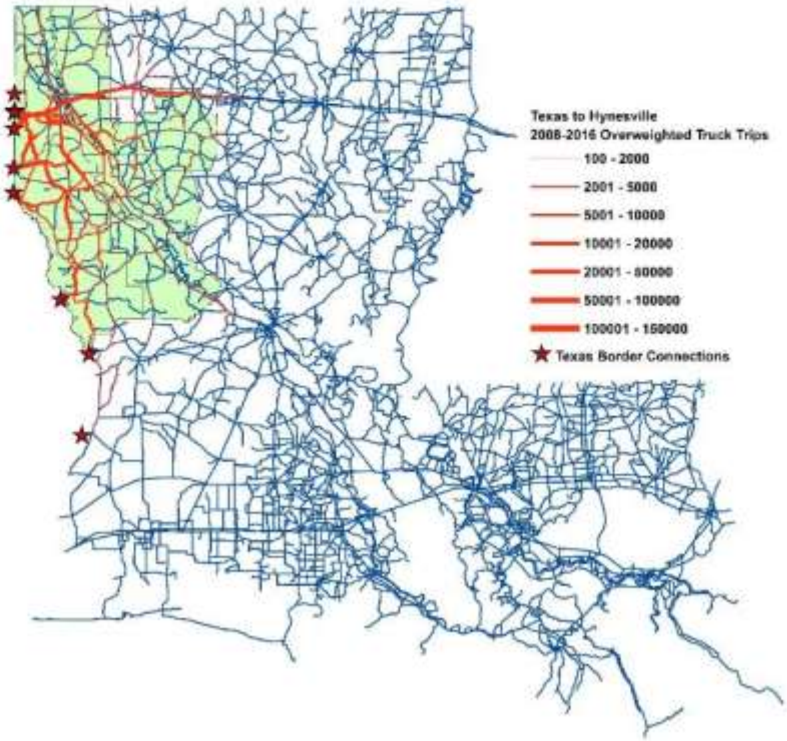


Figure 27
Trips from Texas to the Haynesville area

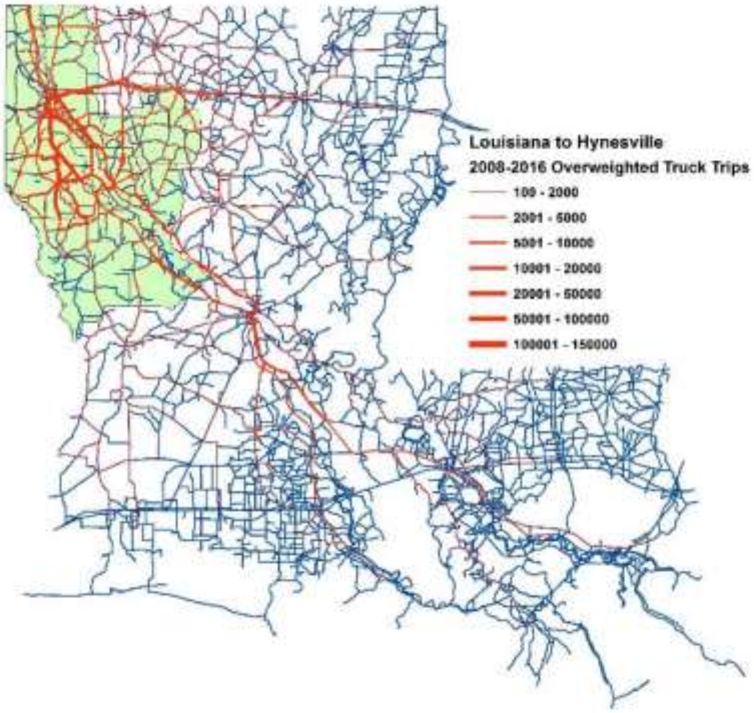


Figure 28
Trips from Louisiana to the Haynesville area

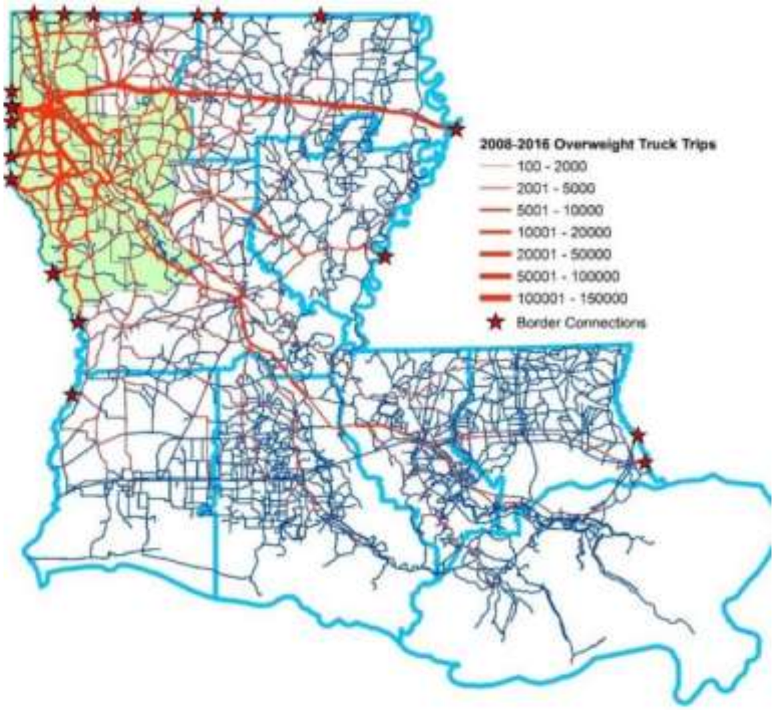


Figure 29
Border connections and distribution of overweight trips related to Haynesville area

Overweight Vehicle Miles Traveled (VMT)
According to the distribution of overweight trips as shown in Figure 29, the total overweight VMT in each year was determined and tabulated in Table 16. The total overweight VMT related to the Haynesville area approximated 22.6 million miles in 2008 - 2016. By multiplying the percentages as shown in Table 15 with the total overweight VMT in each year, the shale-gas related overweight VMT was then estimated and summarized in Table 16. In Table 16, the VMT related to the shale gas development was also broken down into four categories in terms of roadway classifications, including Interstate, US highway, LA roadway (ADT ≥ 2000), and LA roadway (ADT < 2000). It was found out that the roadway usage was get lower with the decrease of the roadway classification. This result is reasonable under the assumption of shortest path.

Table 16
Overweight VMT related to the shale gas development in 2008 - 2016

Categories		2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
Total Overweight VMT (10^3 miles)		1,958	2,313	3,994	4,056	2,157	2,148	2,561	1,823	1,549	22,558
Overweight VMT related to shale gas development (10^3 miles)	Total	329	881	2,615	2,729	830	743	1,022	437	137	9,725
	Interstate	126	266	757	818	280	276	395	168	50	3,135
	US Highway	104	311	917	925	255	224	317	129	44	3,226
	LA roadway (≥2000)	51	171	531	570	163	138	175	78	24	1,902
	LA roadway (<2000)	48	132	411	416	133	104	134	62	19	1,460

The shale-gas related non-overweight VMT can be roughly estimated by multiplying the shale-gas related overweight VMT by 13. In total, the non-overweight VMT related to the shale gas development was 127.6 million miles in 2008 - 2016, as shown in Table 17.

Table 17
Non-overweight VMT related to the shale gas development in 2008 - 2016

Categories		2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
Non-overweight VMT related to shale gas development (10^3 miles)	Total	4,318	11,562	34,326	35,815	10,898	9,749	13,409	5,738	1,804	127,619
	Interstate	1,648	3,497	9,931	10,737	3,673	3,621	5,187	2,204	651	41,148
	US Highway	1,365	4,084	12,031	12,135	3,342	2,944	4,167	1,697	579	42,344
	LA roadway (≥2000)	674	2,243	6,969	7,482	2,144	1,813	2,295	1,029	319	24,968
	LA roadway (<2000)	631	1,737	5,395	5,461	1,739	1,370	1,761	808	255	19,159

Damage Cost Estimation

Damage Cost of Shale-gas Related Vehicle Traveling One Mile. The total damage cost of shale-gas related overweight vehicles on Louisiana roadways is subject to the VMT and the unite damage cost. Table 18 summarizes the design EASLs and reconstruction costs of the typical Interstate, US highways, Louisiana roadways with ADT ≥2000, and Louisiana roadways with ADT <2000. With the reconstruction costs per lane mile and design ESALs, the cost per ESAL per lane mile was estimated. By multiplying the shale-gas related overweight truck factor (6.41, the detailed calculation is presented in Appendix B) with the unit cost per ESAL, the damage cost per overweight vehicle traveling one mile was determined and shown in Table 18. Obviously, the unit damage cost per overweight trip on a low volume road (ADT<2000) is much higher than that on a high classification highway.

Table 18
Cost per overweight vehicle traveling one mile

Roadway Classification [a]	Design ESALs	Per lane mile (USD)		
		Reconstruction cost	Cost per ESAL	Cost per overweight trip
Interstate	66,000,000	3,000,000	0.05	0.29
US Highway	22,000,000	2,000,000	0.09	0.58
LA roadway (≥2000)	1,200,000	550,000	0.46	2.94
LA roadway (<2000)	300,000	275,000	0.92	5.88

[a] flexible pavements.

Total Damage Cost Caused by the Overweight and Non-Overweight Trips. For each roadway classification, multiplying the overweight VMT in Table 16 with the cost per overweight trip travelling one mile in Table 18 yields the total overweight damage cost, as summarized in Table 19. It was discovered that the total damage cost due to the overweight truck trips of the shale gas development approximated $17 million among 2008 to 2016. The damage cost per year is also summarized in Table 19. As presented in Table 19, more than a half of the damage costs were caused in 2010 and 2011, in which the spud of shale gas wells reached its peak.

Table 19
Damage cost due to shale-gas related overweight trips in the Haynesville area

Trip type	Roadway classification	Damage cost (10^3 USD)									
		2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
Overweight trips related to shale gas development	Interstate	37	78	220	238	81	80	115	49	14	912
	US highway	61	181	533	538	148	131	185	75	26	1,877
	LA roadway (>2000)	151	501	1,557	1,672	479	405	513	230	71	5,580
	LA roadway (<2000)	282	777	2,411	2,441	777	613	787	361	114	8,564
	Total	530	1,536	4,722	4,889	1,486	1,229	1,600	715	225	16,933

Strategy of Damage Cost Recovery

The total VMT and total damage cost provide an overall estimation of the impact of the shale-gas related overweight traffic on Louisiana roadways in 2008 - 2016. To recover the damage cost due to the overweight truck trips related to the shale gas development, one common option is to impose a permit fee per single well and the other is to issue permits per specific trip in terms of the gross weight, truck factor, and traveling distances based on the unit price per mile. The latter is in line with the current permit fee schedule of Louisiana.

Average Damage Cost per Well. Considering that 3,230 wells in the Haynesville area were spudded in this period, the average damage cost per well due to the overweight trips was discovered to be $5,264.

Average Damage Cost per Mile. Considering that a typical overweight trip may travel across different types of roadways, a weighted average of the damage cost per overweight trip mile in terms of the roadway usage of different roadway types was calculated and presented in Table 20. The damage costs per mile due to the overweight trips in terms of the roadway classifications in Table 18 were utilized in the calculation. The weighted damage cost was calculated by equation (16).

$$DC_w = \sum_{i=1}^{4} f_i \cdot DC_i \tag{16}$$

where, f_i = roadway usage of the roadway type i;

DC_i = damage cost per ESAL per mile (or per overweight trip per mile) of roadway type i;

DC_w = weighted damage cost per ESAL per mile (or per overweight trip per mile).

It was found out that the weighted average cost per overweight vehicle mile is $1.74 and that per ESAL mile is $0.27. These average cost per mile or per well may serve as a reference for the damage cost recovery.

Table 20
Weighted average cost per ESAL mile and per overweight trip mile

Roadway Classification	Cost per ESAL mile ($)	Cost per overweight trip mile ($)	VMT_i (10^3 miles)	f_i [a]	Weighted average cost per ESAL mile ($)	Weighted average cost per overweight trip mile ($)
Interstate	0.05	0.29	3,135	0.32	0.27	1.74
US highway	0.09	0.58	3,226	0.33		
LA roadway (≥2000)	0.46	2.94	1,902	0.20		
LA roadway (<2000)	0.92	5.88	1,460	0.15		

[a] $f_i = \frac{VMT_i}{\sum_{i=1}^{4} VMT_i}$.

Comparison with the Current Permit Fee Schedule of Louisiana

In this study, the impact of the shale-gas related overweight trips on Louisiana roadways was estimated from various perspectives, including total VMT, total damage cost, damage cost per single well, and damage cost per ESAL/overweight trip mile. In general, the results of this study were comparable with previous studies [10, 12]. Figure 30 shows the comparison of the cost per mile determined by this study and that in the current permit fee schedule of Louisiana with various vehicle gross weights. In the calculation, a typical shale-gas related overweight truck, including a single axle (12 kips), a tandem axle (40 kips), and a tridem axle {gross weight – 52 kips}, was used to determine the ESALs per truck. The average damage cost per ESAL per mile determined in this study, $0.27, was used to calculate the damage cost per mile under various vehicle gross weights. As indicated in Figure 30, the damage cost per mile determined by this study is slightly higher than the unit price of the current overweight permit fee schedule of Louisiana (see Appendix F). Since the gross weight of most shale-gas related overweight vehicles ranges from 108 to 132 kips, the average damage cost per overweight vehicle obtained in this study, $1.74, is also comparable to the unit price of the current overweight permit fee schedule of Louisiana.

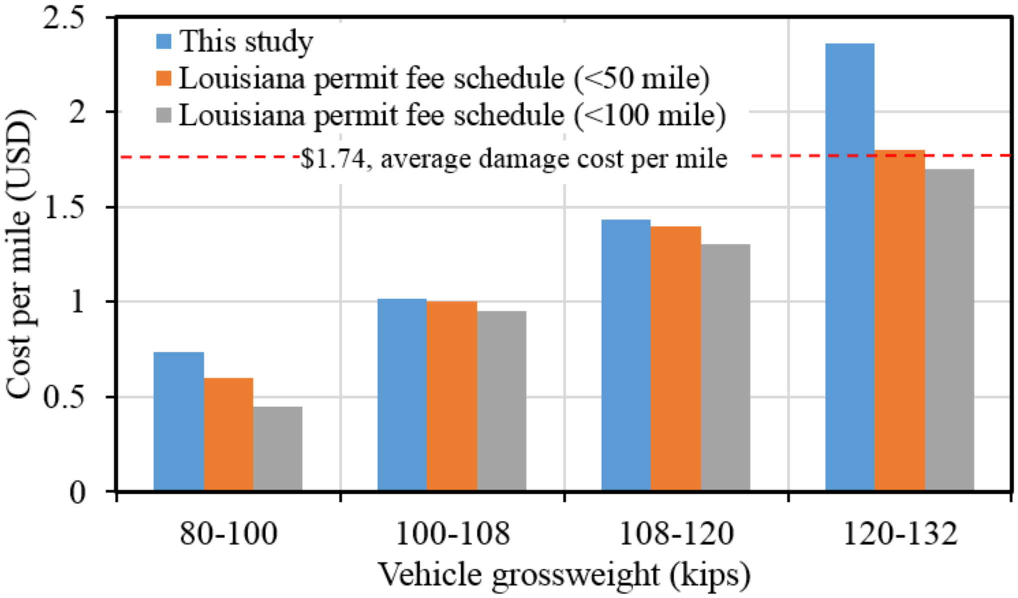


Figure 30
Comparison of the damage cost per mile determined in this study and the unit price of the current permit fee schedule in Louisiana

In addition, the method proposed in this study can also be adopted in the estimation of the impact on roadways by overweight vehicles in other activities, such as agriculture, waste disposal, etc.

Based on network-level analysis, the overweight truck trips on 26 selected damaged routes during the shale gas developing period can be calculated by ArcGIS, which is summarized in Table 50 in Appendix D. Combined with the damage cost per trip obtained for 4 types of routes in network level study (Table 20), the total damage cost for these 26 routes can be estimated. Since a 2-in. asphalt overlay is adopted by DOTD as a typical maintenance method, the estimated total damage cost by overweight truck trips and applied as collected truck permit fee for compensation, are compared with the construction cost of 2-in. overlay ($1.7 per square feet and $10,7712 per mile each lane) as follows. The compensatory rates defined as the ratio between total overweight damage cost and the construction cost of 2-in. overlay are also listed in Table 21.

Table 21
Damage cost on 26 routes with network level analysis results

Route	Control Section	Design AADT	Estimated OW Trips by ArcGIS	Total OW Damage Cost1* ($)	Compensation Ratio (%)
US 171	2507	10800	9032	5238.56	4.86
La 5	4901	5600	9053	26525.29	24.63
La 1	5307	3300	8948	26217.64	24.34
La 157	8201	650	483	2835.21	2.63
La 154	9004	590	1243	7296.41	6.77
La 169	9701	2400	6492	19021.56	17.66
La 5	9802	4500	13588	39812.84	36.96
La 5	9803	2100	9022	26434.46	24.54
La 5	9804	2300	2183	6396.19	5.94
La 191	9903	700	1672	9814.64	9.11
La 514	10001	345	1866	10953.42	10.17
La 3015	29802	660	1840	10800.8	10.03
La 481	29902	800	507	2976.09	2.76
La 513	30004	350	784	4602.08	4.27
La 346	30030	312	175	1027.25	0.95
La 512	30102	156	4369	25646.03	23.81
La 346	30103	452	494	2899.78	2.69
La 515	30202	360	1088	6386.56	5.93
La 783	30302	100	137	804.19	0.75
La 783	30303	190	137	804.19	0.75
La 786	30602	870	294	1725.78	1.60
La 191	43202	622	2352	13806.24	12.82
La 790	80701	160	105	616.35	0.57
La 789	80907	1804	6642	38988.54	36.20
La 789	81609	1380	6598	38730.26	35.96
La 788	84102	500	616	3615.92	3.36
Average	—	—	—	—	11.93

*The damage costs per trip are followed Table 20.

Following the calculated damage costs for four types of routes in Table 20, the total overweight damage cost is obtained by multiple the overweight truck trips from ArcGIS with damage cost per overweight truck trip.

It can be seen that the average calculated compensation ratio of the 26 damaged routes is only 11.93% and below 20% for 19 out of 26 routes; moreover, the average compensation ratio for the low volume routes in Table 21 is only 9%, indicating that for these routes it is inadequate to cover the reconstruction cost with the estimated damage cost as overweight truck permit fee.

The current fee regulation for overweight trucks applied by DOTD is also considered to evaluate the results from network level analysis. The DOTD regulation for overweight truck trips considers the truck gross weight level and travelled distance (see Appendix F). According to the statistical analysis of the issued overweight truck permits, the gross weight distribution of overweight truck trips is summarized in Table 22. Combined with the unit truck permit fee, the weighted average permit fee per overweight as $3.24 per truck trip per mile is obtained in Table 22.

Table 22
Weighted average permit fee for overweight truck trips

Truck Gross Weight (lbs)	Truck Trips	Truck Trip distribution (%)	Current DOTD Unit Fee ($)	Weighted Fee per OW Truck ($)
80,000-100,000	4883	1.67	1.2	0.02
100,001-108,000	73026	25.02	2	0.50
108,001-120,000	124431	42.63	2.8	1.19
120,001-132,000	31596	10.82	3.6	0.39
132,001-152,000	27869	9.55	4.8	0.46
152,001-172,000	25429	8.71	6.2	0.54
172,001-192,000	2684	0.92	7.6	0.07
192,001-212,000	1191	0.41	9	0.04
212,001-232,000	668	0.23	10.4	0.02
232,001-254,000	70	0.02	11.8	0.003
Total	291,847	—	—	3.24

Similarly, the compensatory rates based on the current fee regulation of overweight trucks and trips number obtained from ArcGIS is listed in Table 23. It can be seen that with the currently issued truck permit fee, only 10.38% damage cost would be covered on average for these routes.

Table 23
Damage cost on 26 routes considering network level analysis results and current DOTD permit fee regulation

Route	Control Section	Estimated OW Trips by ArcGIS	Total OW Damage Cost1* ($)	Compensation Ratio (%)
US 171	2507	9032	29263.68	27.17
La 5	4901	9053	29331.72	27.23
La 1	5307	8948	28991.52	26.92
La 157	8201	483	1564.92	1.45
La 154	9004	1243	4027.32	3.74
La 169	9701	6492	21034.08	19.53
La 5	9802	13588	44025.12	40.87

La 5	9803	9022	29231.28	27.14
La 5	9804	2183	7072.92	6.57
La 191	9903	1672	5417.28	5.03
La 514	10001	1866	6045.84	5.61
La 3015	29802	1840	5961.6	5.53
La 481	29902	507	1642.68	1.53
La 513	30004	784	2540.16	2.36
La 346	30030	175	567	0.53
La 512	30102	4369	14155.56	13.14
La 346	30103	494	1600.56	1.49
La 515	30202	1088	3525.12	3.27
La 783	30302	137	443.88	0.41
La 783	30303	137	443.88	0.41
La 786	30602	294	952.56	0.88
La 191	43202	2352	7620.48	7.07
La 790	80701	105	340.2	0.32
La 789	80907	6642	21520.08	19.98
La 789	81609	6598	21377.52	19.85
La 788	84102	616	1995.84	1.85
Average	—	—	—	10.38

* Average damage cost per trip=3.24 USD

The comparison between these two compensatory rates in Table 21 and Table 23 on the 26 damaged routes is shown in Figure 31. The service live of these impacted routes, especially on low volume routes are 4-10 years with the proposed average service life as long as 12-15 years, which indicated that the both of the permit fees (damage costs) estimated by project level are not able to cover the damage due to overweight truck damage.

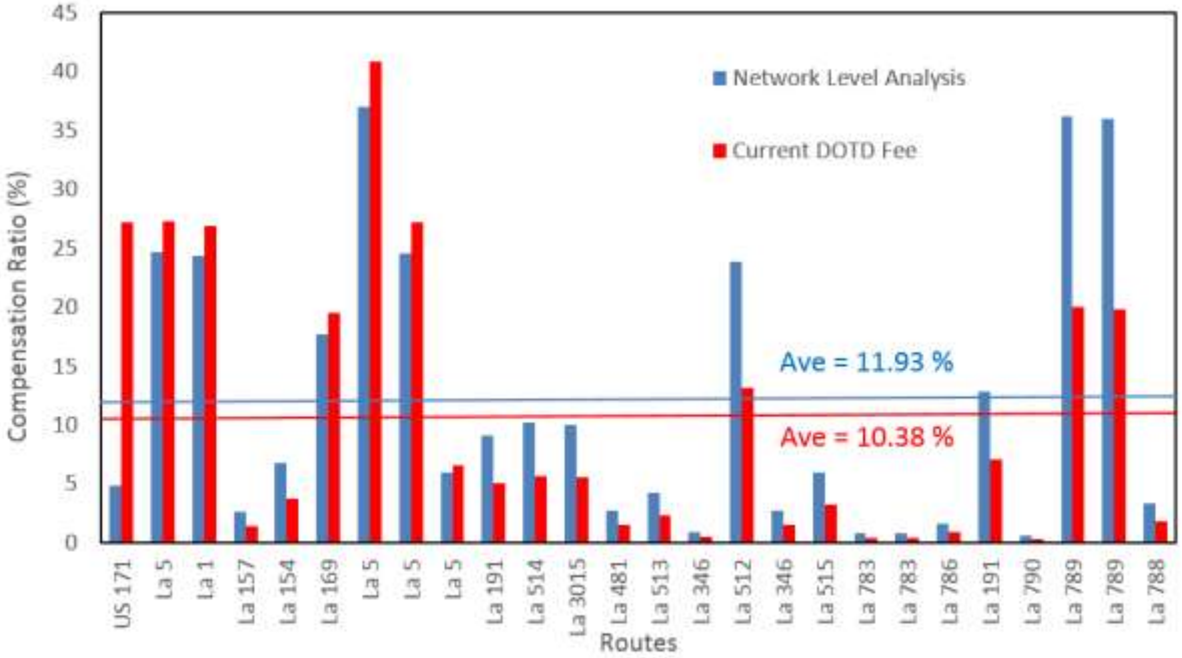


Figure 31
Comparison of the compensatory rates by network level analysis and current DOTD fee

Moreover the details of these routes are not involved in the network level analysis, such as maintenance during the shale gas developing period, pavement structure, traffic conditions and so on. Therefore, the project level analysis considering these factors should be conducted to quantify the actual damage cost for different road types and evaluate their corresponding permit fee.

Project-level Analysis

The network-level analysis in this study estimated the overall impact of the shale-gas related trucks by applying the truck traffic overweight truck traffic trips on Louisiana roadways based on data from issued permits. The VMT in terms of roadway classifications were estimated by shortest path method, and the average damage costs per EASL/trip on four types of routes in Louisiana were obtained. However, the results from the analysis above didn't investigate the actual conditions of damaged routes in Haynesville area. The calculated damage costs are based on EASLs and did not consider the pavement service life economically. Moreover, the obtained average damage cost cannot reflect the influence of gross weight of overweight trucks, which is related to current permit fee regulation developed by DOTD. Therefore project-level study based on the pavement conditions in Louisiana Haynesville area is necessary to refine the results of net-work level analysis.

The overweight truck trips are assigned on 12 damaged routes in Louisiana Haynesville area in a simple way, and the pavement conditions are predicted using MEPDG. The scenarios with/without overweight trucks are compared to quantify the pavement damage costs and the costs for various truck gross weight levels are investigated. Combined with the network level analyzed results, a new set of permit fee regulations can be suggested thereafter.

Estimation of Truck Trips Related to Shale Gas Recovery

Matrix of Interaction Factors. The matrix of interaction factors of the 15 trip estimation zones was determined according to the method introduced in the section of Methodology. Table 24 shows the matrix.

Estimation of Truck Trips. Based on the matrix of interaction factors and number of shale gas wells in each zone, the total truck trips in each zone (assuming 341 truck trips per well) can be estimated thereafter. Table 25 summarizes the estimated truck trips on a single roadway for each zone.

Based on Table 25, the shale-gas related truck trips on the impacted roadways can be determined, as shown in Table 26. The determined results are summarized in Table 26. The estimated overweight trips on the specific roadways (based on 40 overweight trips per well) were calculated and listed in Table 27.

Table 24
Matrix of interaction factors

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.0000	0.2500	0.1000	0.0250	0.0063	0.0833	0.0583	0.0139	0.0036	0.0208	0.0130	0.0000	0.0000	0.0000	0.0000
2	0.1000	1.0000	0.1000	0.0250	0.0000	0.3333	0.0833	0.0139	0.0000	0.0833	0.0185	0.0000	0.0000	0.0104	0.0000
3	0.1000	0.2500	1.0000	0.2500	0.0000	0.1250	0.3750	0.0625	0.0000	0.0521	0.0833	0.0375	0.0113	0.0104	0.0161
4	0.0200	0.0500	0.2000	1.0000	0.2500	0.0417	0.1250	0.1667	0.1429	0.0220	0.0463	0.0333	0.0167	0.0116	0.0143
5	0.0050	0.0125	0.0500	0.2500	1.0000	0.0313	0.0938	0.0417	0.4286	0.0000	0.0208	0.0083	0.0857	0.0000	0.0000
6	0.0500	0.5000	0.1250	0.0313	0.0078	1.0000	0.2500	0.0417	0.0000	0.2500	0.0833	0.0333	0.0000	0.0313	0.0045
7	0.0083	0.1667	0.3000	0.1250	0.0313	0.3333	1.0000	0.1667	0.0070	0.1389	0.2222	0.1000	0.0300	0.0556	0.0429
8	0.0063	0.0208	0.0625	0.1250	0.0313	0.0417	0.1250	1.0000	0.0420	0.0278	0.1111	0.2000	0.1000	0.0278	0.0857
9	0.0025	0.0000	0.0000	0.1250	0.3750	0.0020	0.0061	0.0490	1.0000	0.0050	0.0200	0.0600	0.2000	0.0064	0.0257
10	0.0083	0.0833	0.0125	0.0052	0.0000	0.1667	0.0417	0.0255	0.0029	1.0000	0.1111	0.0333	0.0100	0.1250	0.0357
11	0.0000	0.0208	0.0750	0.0313	0.0078	0.1250	0.2500	0.1667	0.0257	0.2500	1.0000	0.3000	0.0900	0.2500	0.2000
12	0.0000	0.0000	0.0375	0.0417	0.0426	0.0417	0.1250	0.3333	0.0857	0.0833	0.3333	1.0000	0.3000	0.1071	0.4286
13	0.0000	0.0000	0.0000	0.0208	0.1071	0.0125	0.0375	0.1667	0.2857	0.0250	0.1000	0.3000	1.0000	0.0357	0.1429
14	0.0000	0.0208	0.0167	0.0069	0.0000	0.0417	0.0556	0.0370	0.0057	0.2500	0.2222	0.1524	0.0486	1.0000	0.2857
15	0.0000	0.0052	0.0042	0.0125	0.0107	0.0104	0.0514	0.1000	0.0286	0.0625	0.1556	0.3000	0.1000	0.2500	1.0000

Table 25
Estimated truck trips (based on 341 trips per well)

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total trips	Trips per route
1	19437	11253	8696	3069	335	7161	11975	1871	267	931	645	0	0	0	0	65638	13128
2	1944	45012	8696	3069	0	28644	17107	1871	0	3723	922	0	0	622	0	111608	55804
83	1944	11253	86955	30690	0	10742	76981	8418	0	2327	4149	1931	376	622	608	236995	47399
4	389	2251	17391	122760	13384	3581	25660	22449	10668	982	2305	1716	557	691	541	225325	56331
5	97	563	4348	30690	53537	2685	19245	5612	32005	0	1037	429	2864	0	0	153113	38278
6	972	22506	10869	3836	418	85932	51321	5612	0	11168	4149	1716	0	1865	169	200533	66844
7	162	7502	26087	15345	1673	28644	205282	22449	522	6204	11064	5149	1003	3315	1622	336023	84006
8	121	938	5435	15345	1673	3581	25660	134695	3134	1241	5532	10298	3342	1658	3244	215896	71965
9	49	0	0	15345	20076	175	1256	6594	74679	223	996	3089	6684	384	973	130524	37293
10	162	3751	1087	639	0	14322	8553	3430	213	44671	5532	1716	334	7459	1352	93222	46611
11	0	938	6522	3836	418	10742	51321	22449	1920	11168	49786	15447	3008	14919	7570	200043	44454
12	0	0	3261	5115	2279	3581	25660	44898	6401	3723	16595	51491	10025	6394	16222	195644	39129
13	0	0	0	2558	5736	1074	7698	22449	21337	1117	4979	15447	33418	2131	5407	123351	24670
14	0	938	1449	853	0	3581	11405	4989	427	11168	11064	7846	1623	59675	10815	125830	31458
15	0	234	362	1535	574	895	10549	13470	2134	2792	7744	15447	3342	14919	37851	111848	31956

Table 26
Trips related to shale gas activities estimated based on the trip estimation zones (based on 341 trips per well)

Route	**Control section**	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
US 171	2507	3376	14019	25651	18245	6657	3589	5337	2870	4105	83849
La 5	4901	5506	13359	20383	11782	3467	1570	2642	2955	4555	66219
La 1	5307	3071	11956	19881	13154	3763	7587	6113	3073	3343	71939
La 157	8201	3681	7728	14040	10358	4356	4588	6208	4230	1096	56284
La 154	9004	1568	6027	12916	8731	1913	2041	2232	1663	1175	38267
La 169	9701	6267	14936	14675	7528	2226	1588	1918	1651	3140	53928
La 5	9802	5506	13359	20383	11782	3467	1570	2642	2955	4555	66219
La 5	9803	3376	14019	25651	18245	6657	3589	5337	2870	4105	83849
La 5	9804	3376	14019	25651	18245	6657	3589	5337	2870	4105	83849
La 191	9903	2439	10809	14070	9095	1923	759	1032	2728	3600	46455
La 514	10001	1651	6673	11711	7755	1481	2631	1487	1895	2008	37293
La 3015	29802	5506	13359	20383	11782	3467	1570	2642	2955	4555	66219
La 481	29902	1837	9476	13676	10034	2822	1472	1859	1377	1883	44437
La 513	30004	1837	9476	13676	10034	2822	1472	1859	1377	1883	44437
La 346	30030	1084	6568	13117	9252	1987	1874	2175	1459	1614	39129
La 512	30102	789	5393	9008	9188	3844	641	813	967	795	31438
La 346	30103	1084	6568	13117	9252	1987	1874	2175	1459	1614	39129
La 515	30202	1651	6673	11711	7755	1481	2631	1487	1895	2008	37293
La 783	30302	1651	6673	11711	7755	1481	2631	1487	1895	2008	37293
La 783	30303	1568	6027	12916	8731	1913	2041	2232	1663	1175	38267
La 786	30602	1651	6673	11711	7755	1481	2631	1487	1895	2008	37293
La 191	43202	2439	10809	14070	9095	1923	759	1032	2728	3600	46455
La 790	80701	1568	6027	12916	8731	1913	2041	2232	1663	1175	38267
La 789	80907	6267	14936	14675	7528	2226	1588	1918	1651	3140	53928
La 789	81609	6267	14936	14675	7528	2226	1588	1918	1651	3140	53928
La 788	84102	1651	6673	11711	7755	1481	2631	1487	1895	2008	37293

Table 27
Overweight trips related to shale gas activities estimated based on the trip estimation zones (40 overweight trips per well

Route	**Control section**	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
US 171	2507	396	1644	3009	2140	781	421	626	337	482	9836
LA 5	4901	646	1567	2391	1382	407	184	310	347	534	7768
LA 1	5307	360	1402	2332	1543	441	890	717	361	392	8439
LA 157	8201	432	906	1647	1215	511	538	728	496	129	6602
LA 154	9004	184	707	1515	1024	224	239	262	195	138	4489
LA 169	9701	735	1752	1721	883	261	186	225	194	368	6326
LA 5	9802	646	1567	2391	1382	407	184	310	347	534	7768
LA 5	9803	396	1644	3009	2140	781	421	626	337	482	9836
LA 5	9804	396	1644	3009	2140	781	421	626	337	482	9836
LA 191	9903	286	1268	1650	1067	226	89	121	320	422	5449
LA 514	10001	194	783	1374	910	174	309	174	222	236	4374
LA 3015	29802	646	1567	2391	1382	407	184	310	347	534	7768
LA 481	29902	215	1112	1604	1177	331	173	218	162	221	5213
LA 513	30004	215	1112	1604	1177	331	173	218	162	221	5213
LA 346	30030	127	770	1539	1085	233	220	255	171	189	4590
LA 512	30102	93	633	1057	1078	451	75	95	113	93	3688
LA 346	30103	127	770	1539	1085	233	220	255	171	189	4590
LA 515	30202	194	783	1374	910	174	309	174	222	236	4374
LA 783	30302	194	783	1374	910	174	309	174	222	236	4374
LA 783	30303	184	707	1515	1024	224	239	262	195	138	4489
LA 786	30602	194	783	1374	910	174	309	174	222	236	4374
LA 191	43202	286	1268	1650	1067	226	89	121	320	422	5449
LA 790	80701	184	707	1515	1024	224	239	262	195	138	4489
LA 789	80907	735	1752	1721	883	261	186	225	194	368	6326
LA 789	81609	735	1752	1721	883	261	186	225	194	368	6326
LA 788	84102	194	783	1374	910	174	309	174	222	236	4374

Distress Data and Pavement Structure Information

According to the estimated overweight-truck trips shown in Table 24 to 27, the impact of the traffic load generated from the shale gas industry can be analyzed in project level with the detailed structure and distress information.

Pavement ME. The AASHTOWare pavement design software based on MEPDG was applied in this study to quantify the additional influence of shale-gas related truck traffic on the pavement structures of the damaged routes in the Louisiana Haynesville area. Sections for each roadways impacted by the shale gas truck traffic were selected, each consisting of 0.1 mile subsections. The distress data obtained from PMS included average IRI, rutting, alligator cracking, longitudinal cracking and transverse cracking. For the total distress data collected, see Table 28.

Table 28
Distress data from PMS

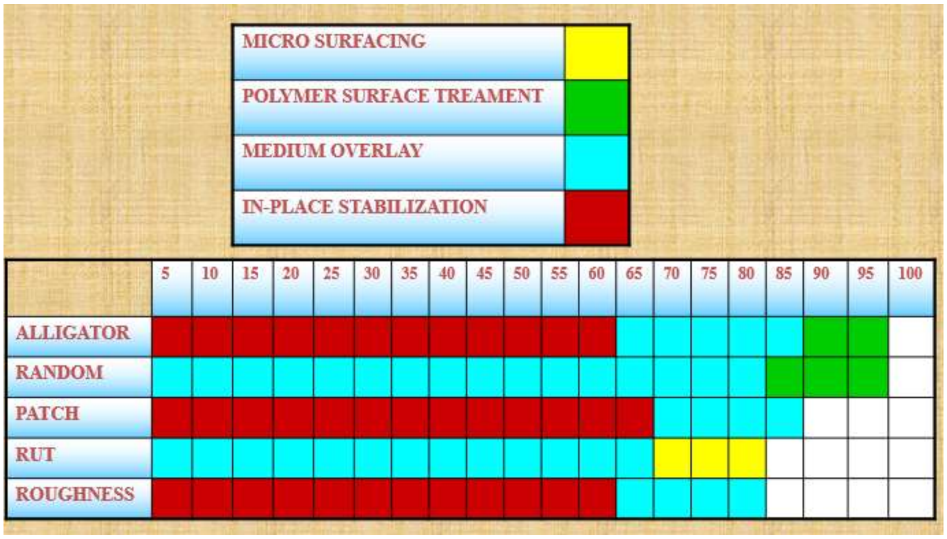
Route	Control Section	Year	IRI	Rutting	Alligator Cracking	Longitudinal Cracking	Transverse Cracking
La 191	099-03	2012	74	0.07	899	34	235
La 514	100-01	2017	191.7	0.33	1629.7	431.6	505.5
La 3015	298-02	2011	139.5	0.23	2274.5	173.5	394.8
La 481	299-02	2012	99.67	0.16	978.0	514.0	32.3
La 513	300-04	2012	149.0	0.09	1163.8	273.0	864.4
La 346	300-30	2017	100	0.08	772.6	56.4	111.8
La 512	301-02	2009	248.0	0.24	740.5	89.5	339.5
La 346	301-03	2017	139.0	0.20	2337.9	553.2	908.8
La 783	303-02	2011	103.5	0.19	2577.7	424.8	1203.8
La 191	432-02	2012	98	0.08	607	48	151
La 789	809-07	2017	154	0.36	1007.3	94.7	577.3
La 788	841-02	2011	190.0	0.27	1086.5	248.0	515.0

There is limitation for total distress such as alligator cracking and transverse cracking to present the pavement damage, due to the various severity levels for collected distress data in PMS. For example in PMS there are four levels of the alligator cracking, including high severity (level 3), medium severity (level 2), low severity (level 1) and no severity (level 0). Therefore distress including index values for alligator cracking (ALCR), random cracking (RNDM), patching (PTCH) roughness (RUFF) and rutting (RUT) are applied to quantify the pavement damage, which are calculated from weighted PMS distress data considering the severity levels. The distress index corresponding to the distress data for the 12 routes are listed in Table 29.

Table 29
Distress index from PMS

Route	Control Section	Investigated logmile	Year	ALCR	RNDM	PTCH	RUFF	RUT
La 191	099-03	5.7-5.8	2012	75.1	87.2	41.5	56.0	98.8
La 514	100-01	1.6-2.5	2017	57.8	67.3	41.6	57.6	78.8
La 3015	298-02	5.4-5.8	2011	53.7	100	78.4	77.4	87.6
La 481	299-02	5.4-5.7	2012	81.4	75.9	82.3	84.8	96.4
La 513	300-04	13.5-14.5	2012	65.3	54.6	100	65.4	99.6
La 346	300-30	0.4-0.5	2017	80.7	95.9	100	89.9	100
La 512	301-02	6.9-7.1	2009	79.5	79.4	83.3	50.2	89.2
La 346	301-03	2.8-3.0	2017	50.0	72.7	100	82.0	93.2
La 783	303-02	2.8-3.4	2011	58.6	73.0	100	85.6	82.0
La 191	432-02	0-0.2	2012	75.4	82.4	73.0	75.8	73.2
La 789	809-07	1.4-1.6	2017	69.6	78.9	69.2	52.2	73.2
La 788	841-02	0-0.2	2011	70.5	79.6	100	63.8	80.4

The pavement life under traffic loading with/without shale-gas related overweight truck was analyzed using AASHTO Pavement-ME Design software.



MICRO SURFACING	🟨
POLYMER SURFACE TREAMENT	🟩
MEDIUM OVERLAY	🟦
IN-PLACE STABILIZATION	🟥

	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
ALLIGATOR	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟩	🟩	
RANDOM	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟩	🟩	🟩	
PATCH	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦			
RUT	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨				
ROUGHNESS	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦				

Figure 32
Pavement maintenance triggers and distress index

The information of pavement structure, such as layer thickness and material properties was collected from Content Manager provided by DOTD. The 90% design reliability and default design criteria in Pavement-ME were adopted, and the climate station “SHREVEPORT_NARR_53905” near Shreveport, LA, was selected as environmental conditions. Local calibration factors were applied according to the previous study by Wu and Xiao [13]. The numbers of overweight truck trips applied are obtained by summing the trips within the simulation period in Table 27. The traffic data and the pavement information obtained from Content Manager database are summarized in Table 30.

Table 30
Overweight trips related to shale gas activities and pavement structures

Route	Control Section	Pavement Structure	Total Overweight trips (40 per well)	Design AADT	Truck Number	Simulation Period
La 191	099-03	2"AC Overlay+2"AC+8.5"CSB	4997	700	6	2000 - 2012
La 514	100-01	2"AC Overlay+3"AC+8.5"CSB	4182	345	10	2009 - 2017
La 3015	298-02	2"AC Overlay+6"AC+8.5"CSB	5986	660	8	2001 - 2011
La 481	299-02	3.5" AC+8.5"CSB	4439	800	12	2007 - 2012
La 513	300-04	2"AC Overlay+3.5"AC+8.5"CSB	4439	350	10	2002 - 2012
La 346	300-30	3.5" AC+12"CTB	1068	312	9	2012 - 2017
La 512	301-02	3.5"AC Overlay+1"AC+8.5"CSB	726	156	8	1998 - 2009
La 346	301-03	3.5"AC Overlay+1.5"AC+8.5"CSB	3692	452	17	2010 - 2017
La 783	303-02	3.5" AC+8.5"CSB	3261	100	8	1995 - 2011
La 191	432-02	3.5" AC+12"CTB	4497	622	8	2005 - 2012
La 789	809-07	3.5"AC Overlay+3.5"AC+8.5"CSB	6325	1804	9	2008 - 2017
La 788	841-02	3"AC Overlay+1"AC+8.5"CSB	3261	500	8	1997 - 2011

Quantifying Overweight Truck Damage on Low-Volume Routes (with MEPDG)

The design AADTT with dimensions such as vehicle class distribution, axles per truck and axle distribution (load spectrum) for TTC Group 1 legal trucks in Louisiana (in Appendix E) was combined with the calculated overweight truck numbers and its dimensions using equations (9-12). This scenario was first simulated in Pavement-ME to calculate the pavement service life with a shale-gas related load (L_1), and the results were matched to the PMS data. The load-related distress in pavement structure such as IRI, transverse cracking and fatigue cracking were considered as criteria. Then the shale-gas related overweight truck number was removed to obtain the corresponding service life without shale-gas related load

(L_0). The reduction in pavement service life L_d, which is the difference between L_1 and L_0 and the service life decrement ratio L_r can be expressed as

$$L_r = \frac{L_d}{L_0} = \frac{L_0 - L_1}{L_0} \tag{17}$$

The obtained equivalent factors and service life reduction for the 12 roads in Louisiana are listed in Table 31.

Table 31
Service life reduction due to shale gas traffic (based on 40 OW trips per well)

Route	Control Section	L_0 (yrs)	L_1 (yrs)	L_d (yrs)	L_r (%)
LA 191	099-03	14.92	10.25	4.67	31.30
LA 514	100-01	14.08	8	6.08	43.18
LA 3015	298-02	16.42	9.92	6.5	39.59
LA 481	299-02	9.17	5.08	4.09	44.60
LA 513	300-04	14.92	9.83	5.09	34.12
LA 346	300-30	9.75	5.42	4.33	44.41
LA 512	301-02	9.42	7.92	1.5	15.92
LA 346	301-03	9.42	6.83	2.59	27.49
LA 783	303-02	14.17	8.42	5.75	40.58
LA 191	432-02	9.25	4.92	4.33	46.81
LA 789	809-07	9.58	7.67	1.91	19.94
LA 788	841-02	17.67	12.92	4.75	26.88

The Equivalent Uniform Annual Cost (EUAC) is also analyzed for these 12 road trips to economically evaluate the impact of shale gas traffic on the Louisiana transportation infrastructures. As is shown in equation (13) the EUAC equals to the cost multiplied by capital recovery. DOTD adopted asphalt overlay as a typical pavement maintenance method, in which the cost is mainly related to the consumed overlay material, therefore the cost in equation (13) is constant ($0.85 per inch per square feet and $53,856 per inch per mile each lane) and the difference of the capital recoveries is applied to evaluate the damage cost due to shale gas development. The capital recovery with and without shale gas development truck load were obtained with 5% interest rate, then the average increased EUAC (Ave. ΔEUAC) due to the shale gas truck traffic per mile for each road trip was obtained according to equation (15).

The damage costs per overweight truck trip and per shale gas well (40 overweight trips per well) for the studied 12 routes were summarized in Table 32. The average damage cost per overweight truck trip is $20.86. The current fee regulation for overweight truck trip is determined by DOTD based on truck type, gross weight and travel distance, which are listed in Appendix F.

Table 32
Average cost per overweight trip mile and per mile of each well

Route	Control Section	ΔEUAC* ($)	Damage Cost per mile per trip ($)
LA 191	099-03	3270.41	6.71
LA 514	100-01	5826.99	11.15
LA 3015	298-02	4265.46	7.07
LA 481	299-02	16804.41	19.23
LA 513	300-04	3721.44	8.24
LA 346	300-30	15663.16	79.49
LA 512	301-02	3826.82	41.75
LA 346	301-03	7677.74	14.20
LA 783	303-02	9092.52	23.48
LA 191	432-02	18214.05	19.93
LA 789	809-07	4948.71	6.00
LA 788	841-02	3293.25	13.05

* Interest Rate=5%

Damage Cost Analysis with AASHTO 93

The impact of the shale gas industry related truck traffic was also investigated based on AASHTO 93 method [21], in which the ratio of damage costs between local truck traffic and shale gas truck traffic was determined by their ESALs. Based on the 12 routes' design AADT and truck numbers obtained from Pavement Content Manager the back-calculated ESALs were determined based on the two truck factors (1.32 and 2.35). The ESALs of the over-weight truck for shale gas development were also calculated with truck factor equals to 6.41. The back-calculated ESALs (1), (2), and (3) are obtained by multiplying (1): Design AADT with Truck Factor 1=1.32; (2): Design AADT with Truck Factor 2=2.35; (3) Overweight truck trips with Truck Factor=6.41.The ESALs of the 12 routes are listed in Table 33.

Table 33
Back-calculated ESAL and over-weight truck ESAL for 12 routes

Route	Control Section	Design AADT	Truck Number	Service Life	Back-calculated ESAL (1)*	Back-calculated ESAL (2)**	OW ESAL*** (40 OW Trips per Well)
La 191	099-03	700	6	10	202356.00	360255.00	32030.77
La 514	100-01	345	10	8	132976.80	236739.00	26806.62
La 3015	298-02	660	8	10	254390.40	452892.00	38370.26
La 481	299-02	800	12	5	231264.00	411720.00	28453.99
La 513	300-04	350	10	10	168630.00	300212.50	28453.99
La 346	300-30	312	9	5	67644.72	120428.10	6845.88
La 512	301-02	156	8	8	48102.91	85637.76	4653.66
La 346	301-03	452	17	7	259150.58	461366.57	23665.72
La 783	303-02	100	8	8	30835.20	54896.00	20903.01
La 191	432-02	622	8	5	119871.84	213408.20	28825.77
La 789	809-07	1804	9	8	625800.38	1114114.32	40543.25
La 788	841-02	500	8	13	250536.00	446030.00	20903.01

* Truck Factor T_{f1}=1.32; ** Truck Factor T_{f2}=2.35; ***Truck Factor T_{fOW}=6.41

Similar to the analysis with Pavement ME, the damage cost was calculated for these 12 routes. The damage costs of overweight truck traffic were calculated by equation (13) for the two truck factors of the AADT. The damage costs of the over-weight truck traffic per mile and per trip in the investigated routes were listed as Table 34. The average damage cost per overweight truck trip per mile on these 12 routes are $6.60.

Table 34
Damage costs of over-weight truck ESAL

Route	Control Section	OW Damage Cost per Mile 1 ($)	OW Damage Cost per Mile 2 ($)	OW Damage Cost per Mile Ave. ($)	OW Damage Cost per Trip 1 ($)	OW Damage Cost per Trip 2 ($)	OW Damage Cost per Trip Ave. ($)
La 191	099-03	14719.68	8794.86	11757.27	2.95	1.76	2.35
La 514	100-01	18070.68	10955.96	14513.32	4.32	2.62	3.47
La 3015	298-02	14117.12	8412.89	11265.01	2.36	1.41	1.88
La 481	299-02	20651.10	12184.87	16417.99	4.65	2.74	3.70
La 513	300-04	15550.91	9325.06	12437.99	3.50	2.10	2.80
La 346	300-30	17323.27	10138.92	13731.10	16.22	9.49	12.86
La 512	301-02	16627.24	9715.17	13171.20	22.90	13.38	18.14
La 346	301-03	15773.11	9197.11	12485.11	4.27	2.49	3.38
La 783	303-02	76155.20	51981.34	64068.27	23.35	15.94	19.65

Route	Control Section	OW Damage Cost per Mile 1 ($)	OW Damage Cost per Mile 2 ($)	OW Damage Cost per Mile Ave. ($)	OW Damage Cost per Trip 1 ($)	OW Damage Cost per Trip 2 ($)	OW Damage Cost per Trip Ave. ($)
La 191	432-02	36540.89	22430.97	29485.93	8.13	4.99	6.56
La 789	809-07	11468.92	6618.62	9043.77	1.81	1.05	1.43
La 788	841-02	12442.05	7232.85	9837.45	3.82	2.22	3.02

The EUAC method was also applied with ESAL on these 12 routes. The service life with shale gas truck traffic (L_0) is determined by PMS data, and the service life without shale gas traffic is calculated by assuming that the pavement will be damaged when achieve same numbers of EASL:

$$L_1 = L_0 \times (1 + \frac{EASL_{OW}}{EASL_{BC}}) \qquad (18)$$

where, $EASL_{OW}$ and $EASL_{BC}$ are overweight truck EASL and Backcalculated EASL listed in Table 33. Two different service life without shale gas traffic L_{1-1} and L_{1-2} were obtained based on truck factor 1.32 and 2.35. The calculated damage cost per OW trip per mile are listed in Table 35 with average value equals to $6.55.

Table 35
Damage costs of over-weight truck based on ESAL and EUAC

Route	Control Section	L_0 (yrs)	L_{1-1} (yrs)	L_{1-2} (yrs)	OW Damage Cost per Trip 1 ($)	OW Damage Cost per Trip 2 ($)	OW Damage Cost per Trip Ave. ($)
La 191	099-03	10	11.58	10.89	2.95	1.77	2.36
La 514	100-01	8	9.61	8.91	4.29	2.61	3.45
La 3015	298-02	10	11.51	10.85	2.36	1.41	1.89
La 481	299-02	5	5.62	5.35	4.74	2.80	3.77
La 513	300-04	10	11.69	10.95	3.18	1.91	2.54
La 346	300-30	5	5.51	5.28	12.08	7.07	9.57
La 512	301-02	8	8.77	8.43	23.15	13.53	18.34
La 346	301-03	7	7.64	7.36	4.12	2.40	3.26
La 783	303-02	8	13.42	11.05	25.64	17.57	21.60
La 191	432-02	5	6.20	5.68	8.86	5.44	7.15
La 789	809-07	8	8.52	8.29	1.83	1.06	1.45
La 788	841-02	13	14.08	13.61	4.13	2.40	3.27

* Truck Factor T_{f1}=1.32; ** Truck Factor T_{f2}=2.35

The comparison between results from AASHTO 93 and MEPDG are plotted in Figure 33.

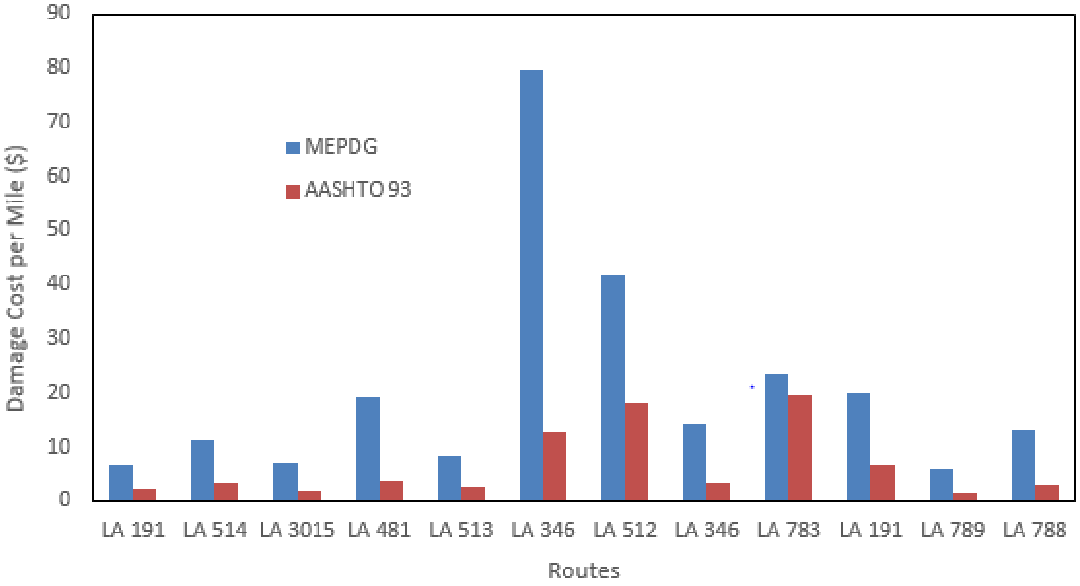


Figure 33
Damage costs for 12 routes by AASHTO 93 and MEPDG

From the results, it can be seen that the unit damage cost ($ per trip per mile) based on EASL ($6.55-6.60) is close to the unit damage cost of low volume roads ($5.88) in network level analysis. However the unit damage cost obtained from Pavement M-E is significantly higher than those from EASL method ($20.86). This is mainly because:

- The TTC Group 1 load spectrum is adopted as legal truck traffic in analysis with MEPDG. The truck load of TTC Group 1 is much lighter than the load of national default spectrum, which amplified the damage of overweight truck trips generated from shale gas recovery activities.
- According to previous studies [22] about damage cost on Louisiana low volume roads due to sugarcane heavy trucks, the permit fee could be raised from $100 per year to $5500 per year if the truck gross weight increase from 80 kips to 100 kips; moreover, the annual permit fee could be more than $9950 for trucks with gross weight as 120 kips. In this study (Figure 22) for most overweight truck trips (42.6%) the gross weight is around 120 kips, and 73.3% of the total overweight truck trips the gross weight is equal to or greater than 120 kips, which can explain the high damage cost due to shale gas development.

Based on the results obtained from project level analysis by both MEPDG and AASHTO 93 methods, the compensation ratios of these results are checked again to determine if the calculated damage cost could cover the reconstruction investment of these routes impacted by shale gas recovery.

Table 36 summarizes the compensation ratios on the 12 routes obtained from MEPDG and AASHTO 93 methods. The total fees collected in Table 36 equal the total OW trips on the 12 routes multiplied with the damage costs in Table 32 and Table 35.

Table 36
Compensation ratios on the 12 routes

Route	Control Section	Total OW Trips	Total Fee Collected MEPDG ($)	Compensation Ratio (%)	Total Fee Collected AASHTO ($)	Compensation Ratio (%)
LA 191	099-03	4997	33529.87	24.4	11792.92	8.6
LA 514	100-01	4182	46629.3	33.9	14427.9	10.5
LA 3015	298-02	5986	42321.02	30.8	11313.54	8.2
LA 481	299-02	4439	85361.97	62.1	16735.03	12.2
LA 513	300-04	4439	36577.36	26.6	11275.06	8.2
LA 346	300-30	1068	84895.32	61.7	10220.76	7.4
LA 512	301-02	726	30310.5	22.0	13314.84	9.7
LA 346	301-03	3692	52426.4	38.1	12035.92	8.8
LA 783	303-02	3261	76568.28	55.7	70437.6	51.2
LA 191	432-02	4497	89625.21	65.2	32153.55	23.4
LA 789	809-07	6325	37950.0	27.6	9171.25	6.7
LA 788	841-02	3261	42556.05	30.9	10663.47	7.8
Average	—	—	—	39.9	—	13.5

According to the damage cost estimated by DOTD (Table 4), it can be seen that, for most of the damage routes, the cost per mile per lane is $137,500. The compensation ratios are calculated by dividing the total fee collected with this $137,500 damage cost. The average compensation ratios on the 12 routes are 39.9% based on MEPDG method and 13.5% for AASHTO method. From the network level analysis there were 331,528 OW trips in Haynesville area during 2006 - 2016 and among them 129,502 trips are related to shale gas development, which equals to 39.06% and means that the OW trucks . Therefore it can be concluded that the results obtained from the AASHTO 93 method on project level analysis is not adequate to cover the road damage cost and the MEPDG results are sufficient for covering the impact due to the oil gas development along with the permit fee paid by trucks from other industries. Therefore the damage cost obtained from network-level with MEPDG method is selected for updating the current DOTD permit fee regulation.

Permitting for Shale Gas Overweight Trucks in Louisiana

Permit Fee Considering Truck Gross Weight and Travel Distance. The current fee regulation for overweight trucks is determined by truck gross weight and travel distance. The overweight trucks with gross weight ranging from 80,000 to 254,000 lbs. are categorized into 10 levels, combined with the five travel distance levels. More details about current overweight truck fee regulation can be found in Appendix F

Gross Vehicle Weight (GVW) and Damage Costs for Shale-gas Related Overweight Trucks. In order to obtain the damage cost of the shale-gas related overweight trucks considering gross truck weights, the heavy equipment transported with trucks involved during oil gas recovery were simulated with MEPDG.

The FHWA Type 10 Trucks (Six or More Axle Single-Trailer Trucks) were selected as typical vehicle for shale gas industry, due to the fact that 84.21% of shale gas overweight trucks are Type 10 Truck (Table 11). Five types of heavy trucks for oil gas well construction such as drilling/workover rigs, fracturing units, coiled tubing units (CTU), nitrogen pumper and truck transported equipment (for example, excavator and drilling rig) are studied in this research, with the details of make and model and total weight of equipment summarized in Table 37. Note that for the truck transported equipment, it is assumed that a double drop 7 axle trailer with 32 kips in weight is adopted and added to total weight. The figures of the listed equipment can be found in Appendix G.

Table 37
Construction equipment for shale gas recovery

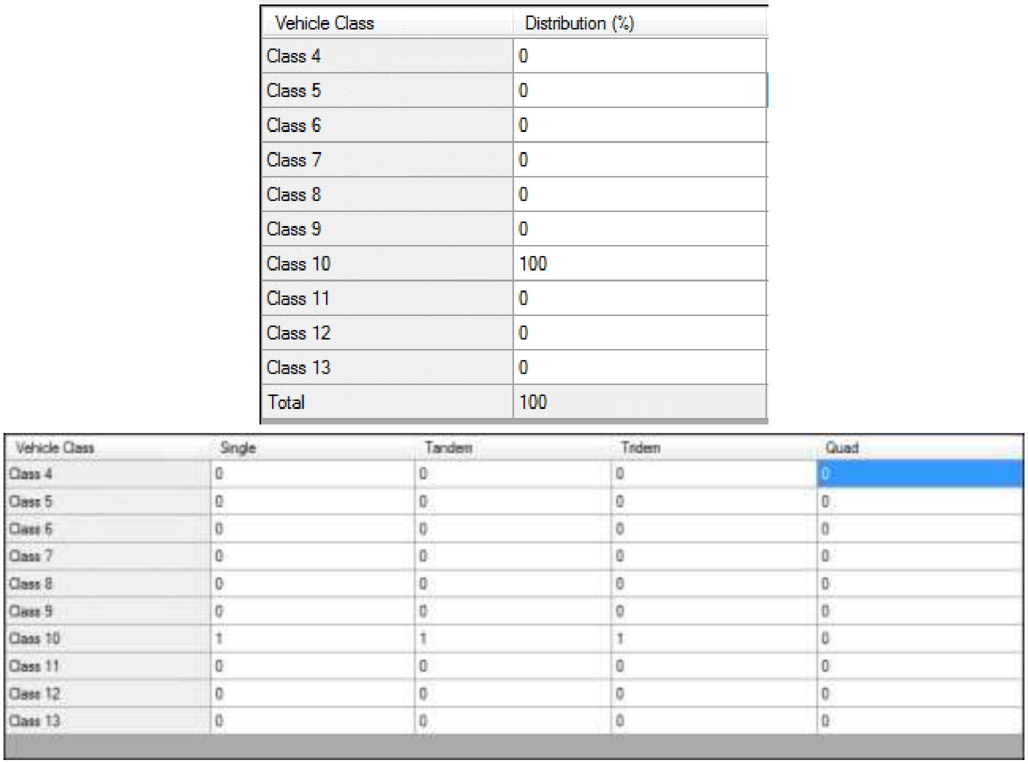
Type	Make & Model		Total Weight	Figure
1. Drilling/ Workover Rigs	ZJ 30 Truck-Mounted Drilling Rig		180.4 kips	39(a), 39(b)
	ZJ 10/900CZ Truck Mounted Drilling Rig		110 kips	40
	XJ Truck Mounted Workover Rig	XJ 350	92.4 kips	41
		XJ 150	167.2 kips	
		XJ 120	121 kips	42
		XJ 100	116.6 kips	
		XJ 80	113.3 kips	
		XJ 60	112.2 kips	
		XJ 40	83.6 kips	
		XJ 550	118.8 kips	43(a), 43(b)
2. Fracturing Units	YLC140-5600 Truck Mounted Fracturing Unit		81.8 kips	44
	ACEWEL 2500 Truck-mounted Fracturing Pump		99 kips	45
	YLC105-2250 Truck Mounted Fracturing Unit		83.8 kips	46
3. Coiled Tube Units	SERVA Coiled Tube Units 0.175 Tube Wall 0.156 Tube Wall 0.134 Tube Wall		170.8 kips 164.0 kips 156.0 kips	47
	Jereh LGT450 Trailer Mounted Coiled Tubing Unit		120 kips	48(a) 48(b)

4. Nitrogen Pumper	Weber trailer mounted 180K N2 pumper	85 kips	49
	PENT-640 K truck mounted direct-fired nitrogen unit	88.2 kips	50(a) 50(b)
5. Equipment Transported with Truck	Case CX470B excavator	135.8 kips	51
	Case CX490D excavator	141.3 kips	52
	Caterpillar 349F XE excavator	145.6 kips	53
	AF 190/ AF 180D Drilling rig	151 kips	54
	AF 12 Drilling Rig	129 kips	55

DOTD regulates the limits of axle groups for overweight trucks, in which several axle group configurations are taken into consideration (Appendix F). The limits of axle group weight is also different for Interstate and LA local routes. For example, for a FHWA Type 9 truck (Five Axle Single-Trailer Trucks) with a single axle (steering axle) and two tandem axles, the limit on Interstate is 12 kips for the single axle and 34 kips for each tandem axle (12+34+34), while for LA local routes it is 12 kips for the single axle and 48 kips for each tandem axle (12+48+48); For the FHWA Type 10 trucks (Six or More Axle Single-Trailer Trucks), the weight limit of tridem axle is 42 kips for Interstate and 60 kips for LA local routes, and for quad axle it is 50 kips and 80 kips for Interstate and LA local routes. More details about the axle weight limits can be found in Figure 38.

The equipment listed in Table 37 are simulated in AASHTOWare considering their total weights and the DOTD regulations about axles on LA local routes, based on the fact that the pavement structures investigated in this study are all low volume routes.

Figure 34 shows an example of the input for the vehicle class distribution and axle per truck of FHWA type 10 truck, which has a single (12 kips), a tandem (40 kips) and a tridem axle (60 kips) in AASHTO Pavement-ME software. Similarly, the load spectrum for single axle distribution is 100 in the row of class 10 and column of 12000 lbs, all the other slots are 0; For tandem axle distribution, the value is 100 in the row of class 10 and column of 40000 lbs, all the other slots are 0; For tridem axle distribution, the value is 100 in the row of class 10 and column of 60000 lbs, all the other slots are 0. If there is no options for the desired weight in spectrum, then the most closed two load values were selected and combined to obtained the desired value. For example, for tridem axle load equals to 38,000 lbs, the 38,000 were obtained from 33.33% of 36,000 lbs and 66.66% of 39000-lbs axle loads.



Vehicle Class	Distribution (%)
Class 4	0
Class 5	0
Class 6	0
Class 7	0
Class 8	0
Class 9	0
Class 10	100
Class 11	0
Class 12	0
Class 13	0
Total	100

Vehicle Class	Single	Tandem	Tridem	Quad
Class 4	0	0	0	0
Class 5	0	0	0	0
Class 6	0	0	0	0
Class 7	0	0	0	0
Class 8	0	0	0	0
Class 9	0	0	0	0
Class 10	1	1	1	0
Class 11	0	0	0	0
Class 12	0	0	0	0
Class 13	0	0	0	0

Figure 34
Vehicle class distribution and axle per truck of FHWA Type 10 truck

A semi-rigid pavement structure with 3.5-in. asphalt surface layer and 8.5-in. cement stabilized soil base was applied, which is typical design in LA low volume routes and closed to the pavement structures of the 12 routes in this study. Then all overweight trucks with various gross weights (Table 58) and the combined shale gas overweight truck (Table 11) are applied as truck traffic input. In previous analysis the daily traffic of overweight truck is about 0.5~1.5, therefore the AADTT in all these cases is set as 10, which is the minimum value allowed in AASHTOWare.

The pavement structures in all the cases are defined as damaged with same criteria, the number of a specific truck gross weight to reach this criteria can be obtained by multiple service life with AADTT (=10). Since the total damage cost of a route is constant, the damage cost per truck trip for a specific truck gross weight can be estimated by dividing it with the total damage cost. With the 20.86$ average damage cost obtained from the 12 routes in Louisiana, the damage cost per trip for each truck in Table 33 is shown in Figure 35 as follows.

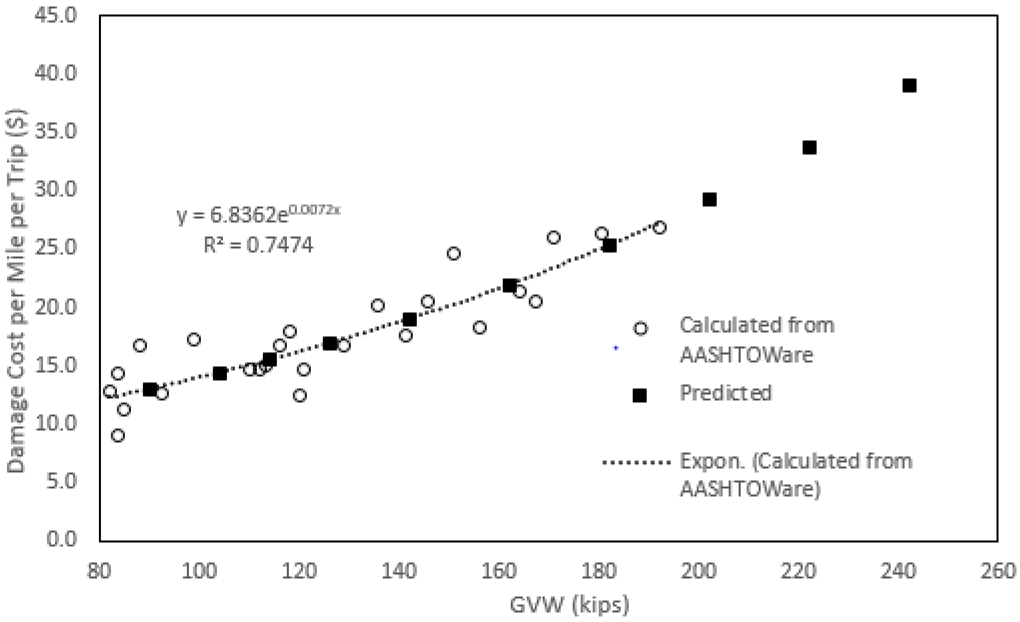


Figure 35
Damage costs for shale-gas related overweight trucks

As is shown in Figure 35, the equipment listed in Table 33 with GVW various from 80-200 kips were calculated in AASHTOWare and the results are plotted with an exponential regression curve (R^2=0.7474). The relationship between the GVW of the shale-gas related overweight trucks and their damage cost per mile per trips is found to be:

$$\mathrm{DMG} = 6.8362e^{0.0072\mathrm{GVW}} \qquad (19)$$

where, DMG is damage cost per mile per trip ($) and GVW is gross vehicle weight (kips). The current fee regulation for overweight truck is determined by truck gross weight and travel distance. For the GVW, the overweight trucks are divided into 10 ranges listed in Table 38. By submitting these average values of the GVW ranges into equation (19), the average damage costs per mile per trip of these GVW ranges can be obtained, which are listed in Table 38.

Table 38
Damage costs for truck gross weight ranges in 12 routes

Gross Vehicle Weight (lbs)	Average Gross Weight (lbs)	Damage Cost per Trip per Mile ($)
80,000-100,000	90,000	13.07
100,001-108,000	104,000	14.45

Gross Vehicle Weight (lbs)	Average Gross Weight (lbs)	Damage Cost per Trip per Mile ($)
108,001-120,000	114,000	15.53
120,001-132,000	126,000	16.94
132,001-152,000	142,000	19.00
152,001-172,000	162,000	21.95
172,001-192,000	182,000	25.35
192,001-212,000	202,000	29.27
212,001-232,000	222,000	33.81
232,001-254,000	242,000	39.04
Combined OW*	—	20.86

* Details of combined overweight trucks can be found in Table 11

Based on the damage cost summarized in Table 38, the permit fee regulation of various truck gross weight levels on LA low volume roadway (with annual average daily traffic less than 2000) is determined as is shown in Table 39, considering the fee ratios applied with various travel distances in current permit fee regulation. The permit fee for travel distance from 0-50 miles is obtained by multiple damage cost per mile by 50, and the permit fee for other travel distances are obtained from the ratio among permit fees in Appendix F.

Table 39
Permit fee about shale gas truck gross weights on LA roadway (AADT<2000)

Truck Gross Weight (lbs.)	Distance (miles)				
	0-50	51-100	101-150	151-200	Over 200
80,000-100,000	$653.44	$980.16	$1415.79	$1742.51	$2178.14
100,001-108,000	722.74	1373.21	1951.41	2601.88	3180.07
108,001-120,000	776.70	1442.44	2108.19	2773.93	3439.67
120,001-132,000	846.79	1599.50	2352.20	3104.90	3904.65
132,001-152,000	950.18	1781.59	2652.60	3523.60	4394.60
152,001-172,000	1097.35	2088.51	3115.06	4141.62	5168.17
172,001-192,000	1267.31	2434.58	3635.19	4835.80	6036.42
192,001-212,000	1463.60	2829.63	4228.18	5626.73	7025.28
212,001-232,000	1690.29	3283.06	4908.34	6533.62	8126.39
232,001-254,000	1952.09	3804.92	5690.83	7576.75	9396.49

According to the results from network analysis listed in Table 18, the costs per overweight trip for LA low volume roadway (AADT<2000), LA roadway with medium traffic volume (AADT ≥2000), US highway and Interstate are \$5.88, \$2.94, \$0.58, and \$0.29. By assuming that the fee regulation for these four types of routes follow this ratio, the permit fee about truck gross weight ranges on LA roadway (AADT≥2000), US highway and Interstate are calculated and listed in Table 59-61 in Appendix H. The weighted average cost per overweight trip mile for all four types of routes in Louisiana is $1.74 obtained from network level analysis, compared with the $5.88 damage cost per mile for LA low volume roadway (AADT<2000), the weighted average cost per overweight trip mile for combined all four types of routes is listed in Table 40.

Table 40
Recommended permit fee about shale gas truck gross weights on LA roadway

Truck Gross Weight (lbs.)	Distance (miles)				
	0-50	51-100	101-150	151-200	Over 200
80,000-100,000	$193.36	$290.05	$418.96	$515.64	$644.55
100,001-108,000	213.87	406.36	577.46	769.94	941.04
108,001-120,000	229.84	426.84	623.85	820.86	1017.86
120,001-132,000	250.58	473.32	696.06	918.80	1155.46
132,001-152,000	281.18	527.21	784.95	1042.70	1300.44
152,001-172,000	324.73	618.03	921.80	1225.58	1529.36
172,001-192,000	375.02	720.44	1075.72	1431.00	1786.29
192,001-212,000	433.11	837.34	1251.20	1665.05	2078.91
212,001-232,000	500.19	971.52	1452.47	1933.42	2404.75
232,001-254,000	577.66	1125.95	1684.02	2242.10	2780.59

The comparison between the current overweight truck permit fee (0-50 miles) and the corresponding new regulation is shown in Figure 36. It can be seen that the permit fee suggested in this study is generally larger than it is in the current DOTD overweight truck fee regulation. This difference is very significant especially when the GVW is between 80-152 kips.

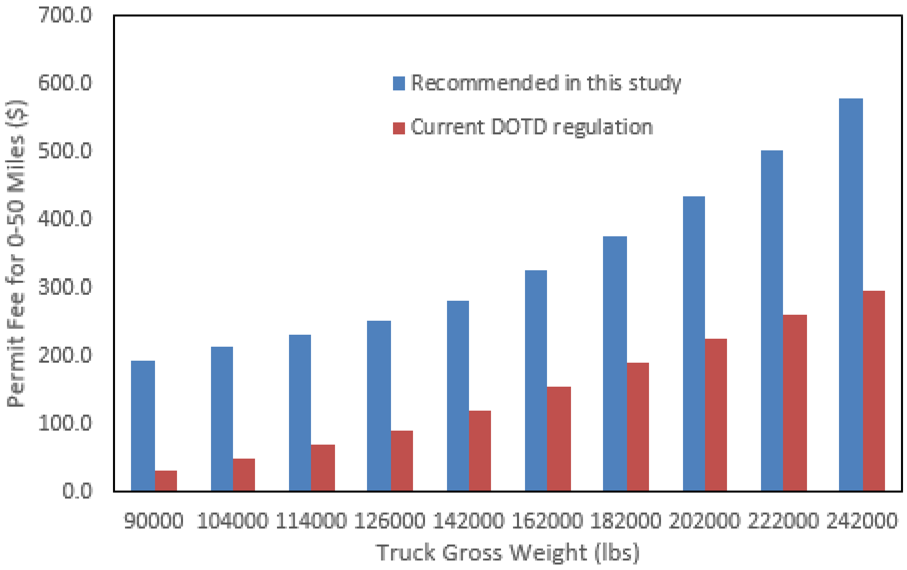


Figure 36
Comparison of current DOTD permit fee and suggested regulation

Fees of Single/Annual Permits for Overweight Trucks. The overweight truck permits for single trip are issued in 21 states; however, DOTD does not specifically regulates this type of permits for overweight trucks. According to the network-level analysis, the distribution of the distance travelled for overweight truck trips is summarized in Table 41 as follows

Table 41
Distribution of miles travelled of overweight truck trips

Miles Travelled (miles)	30	50	70	90	110	130	150	> 150
Truck Trips	18218	162017	67652	5727	13204	765	1453	22852
Percentage (%)	6.24	55.51	23.18	1.96	4.52	0.26	0.50	7.83

It is assumed that the average travelled distance over 150 miles is 200 miles, the weighted average travelled distance 69.3 miles for the overweight truck trips can be obtained by multiple the average travelled distance by the percentage of truck trips. Therefore the weighted average travelled distance as 70 miles is suggested in this study.

Currently DOTD only issues annual permit for overweight truck with gross weight from 80,000 to 120,000 lbs, and the fee for annual permit is $2,500 regardless the level of the truck gross weight. Previous research conducted by Ohio DOT [23] indicated that 24.3 truck trips would be operated for an overweight truck after an annual permit was applied, therefore the annual fee for a specific truck gross weight level can be estimated by the single trip fee by 24.3. It is suggested that the permit fee for single trip considering the GVW is obtained by multiplying the damage cost per mile per trip in LA roadways (obtained from the damage cost per mile per trip in Table 34 and the ratio in Table 20) with 69.3 miles. Similarly the annual permit fee is equal to damage cost of single trip times 24.3 trips/year. The single and annual permit fee regulation for various gross truck weight ranges are recommended in Table 42 as follows.

Table 42
Recommend fee of single/annual overweight truck permit

Truck Gross Weight (lbs.)	Damage Cost per Mile per Trip of LA roadway	Single Trip Permit	Annual Permit
80,000-100,000	$3.9	$271.2	$6589.5
100,001-108,000	4.3	299.9	7288.4
108,001-120,000	4.6	322.3	7832.5
120,001-132,000	5.0	351.4	8539.3
132,001-152,000	5.6	394.3	9581.9

Truck Gross Weight (lbs.)	Damage Cost per Mile per Trip of LA roadway	Single Trip Permit	Annual Permit
152,001-172,000	6.5	455.4	11066.0
172,001-192,000	7.5	525.9	12780.0
192,001-212,000	8.7	607.4	14759.4
212,001-232,000	10.0	701.5	17045.4
232,001-254,000	11.6	810.1	19685.4

Summary

The results of project level analysis are summarized as follows:

- The current fee regulation in LA only considers ranges of VMT and GVW, underestimating the overweight truck damage. The relationship between GVW and the unit fee did not reflect the actual condition in which the damage cost was underestimated with GVW ranging from 80-152 kips (Figure 36). Therefore Table 40 is recommended as the new combined fee regulation based on this study. Combined with the distribution of VMT for each GVW level, the single/annual overweight permit fee is recommended in Table 42 as well.
- The condition of pavement structure is not considered in current highway cost allocation. The damage cost for the overweight truck is different for the four categories of roadway type in this study, which is related to the permit fee per overweight truck trip. This study also recommends the permit fee regulations for specific route types (Interstates, US highway, and LA local routes), as is summarized in Appendix H.
- The relationship between overweight truck gross weight and pavement conditions could be applied on GIS, and a system for determining accurate truck permit fee based on truck information (gross weight, truck type, axle distribution etc.) and pavement conditions of involved routes could be therefore built up.

CONCLUSIONS

In this study, the impact of the shale gas development in the Haynesville area on Louisiana roadways was investigated by using the overweight permits data. RStudio was employed as a major tool to extract and reformat the data regarding overweight trips in 2006 - 2016. Network Analyst in ArcGIS was then used to assign the overweight trips to the Louisiana roadway network according to the shortest path method. The assigned overweight trips were not only utilized for the analysis of the impact of overweight trips, but also served as a sample of all the truck trips in the shale gas development, including the non-overweight trips. With the distribution of overweight trips on the Louisiana roadway network, the vehicle miles traveled (VMT) was calculated in terms of roadway classification and the damage costs were estimated thereafter.

A matrix approach based on the shale gas well numbers and traffic interconnections was also developed to quantify the distribution of relevant truck trips on the impacted roadways; the load spectrum of both overweight and legal truck load was combined in AASHTO and Pavement M-E design to quantify the damage due to overweight truck. Researchers selected 12 damaged roads in the shale gas area, with three sections in each route analyzed considering the conditions with or without shale-gas related truck trips, the results were compared to the field monitoring database from Pavement Management System (PMS). Then pavement life cycle cost analysis was conducted to calculate the damage cost due to shale gas truck traffic during energy development activities. The damage costs of heavy equipment truck for shale gas development were investigated, the obtained results were applied to recommend permit fee regulations for overweight truck trips.

Conclusions from the Network-level analysis:

- It is feasible to investigate the impact of the overweight trips in the shale gas development on roadways by using RStudio and ArcGIS based on the overweight Permit database. The methodology adopted in this study can be used for other permit types, such as mining, seasonal agricultural activities, oversize trips, etc.
- It was estimated that there were 130 thousand overweight trips related to the shale gas development in the Haynesville area during the dramatic rise of the shale gas industry during 2008 - 2016. The VMT of these overweight trips approximated 9.7 million miles on the Louisiana roadway system. With an estimated overweight truck factor of 6.41, and the unit costs per mile on different types of roadways, the VMT was translated into a damage cost of $17 million.

- On average, the damage cost due to the overweight trips in the construction of a single well approximates \$5,264 and the damage cost per overweight mile approximates \$1.74. These average costs may serve as a reference for the future damage cost recovery.

Conclusions from the Project-level analysis:

- Overweight truck traffic could be obtained based on zone interaction analysis and shale gas well numbers. This method is suitable especially under the conditions that the truck permit information is unavailable.
- The AADTT, truck type distribution, axles per truck, and axle load spectrum for Louisiana local trucks and shale gas overweight trucks were combined as input in Pavement ME. Based on Pavement ME analysis, the average damage cost per overweight truck is \$20.86 per trip mile on the 12 selected LA low volume routes (AADT<2000).
- The results obtained from Pavement ME are compared to the results from AASHTO 93 method. It was found that the damage costs obtained by AASHTO 93 is not adequate to compensate the reconstruction investment, if it is adopted as future permit fee. The Pavement ME results are recommended for updating the permit fee regulation.
- The equipment trucks with various GVWs were investigated considering DOTD regulation about axle configurations. The damage cost per truck mile on GVW ranges within 80-252 kips were obtained, and a new permit fee regulation involved GVW and travel distances following the current overweight truck permit fee schedule was suggested.
- In addition, single trip permit and annual permit with various GVW levels are also recommended.

RECOMMENDATIONS

This research project developed a network level analysis method to estimate the traffic impact of overweight truck traffic on Louisiana roadways, which is based on overweight/oversize permit database and ArcGIS. This method is convenient for summarizing the vehicle miles travelled (VMT) into desired roadway categories and therefore the damage cost for each roadway type could be obtained correspondingly. It is recommended that DOTD adopt this method for analysis of other permit types such as seasonal agricultural activities, oversize trips, etc.

In addition, a new permit fee schedule considering gross vehicle weight (GVW) and travelling distance is recommended, based on the damage costs obtained from project level analysis on LA low volume routes (AADT<2000) and the statistic from network level analysis. It is suggested that DOTD consider this permit fee schedule in making overweight truck related policy.

Furthermore, it is recommended that the DOTD truck permit database should include more information (for example, actual routes travelled and frequency of annual overweight permit) in the future to develop a more detailed network level analysis. Studies on other roadway types (Interstate, US highway, and LA routes with AADT over 2000) should also be pursed to improve the recommended permit fee regulation.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AADT	annual average daily traffic
AADTT	annual average daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	average daily traffic
ALCR	alligator cracking index
cm	centimeter(s)
CSV	comma separated values
CTU	coiled tubing unit
DMG	damage cost
DNR	Department of Natural Resource
DOTD	Department of Transportation and Development
DOT	Department of Transportation
EUAC	equivalent uniform annual cost
ESAL	equivalent single axle load
FHWA	Federal Highway Administration
ft.	foot (feet)
FWD	the falling weight deflectometer
GIS	geographic information system
GPS	global positioning system
GVW	gross vehicle weight
HCAS	highway cost allocation study
in.	inch(es)
IRI	the international roughness index
LA	Louisiana
LTRC	Louisiana Transportation Research Center
lb.	pound(s)
m	meter(s)
MEPDG	Mechanistic-Empirical Pavement Design Guide
NAPCOM	National Pavement Cost Model
NCHRP	National Cooperative Highway Research Program
O-D	origin-destination
OS/OW	oversize/overweight
PTCH	patching index
PMS	pavement management system

RNDM	random cracking index
RUFF	roughness index
RUT	rutting index
SN	structural number
TAZ	traffic analysis zone
TTC	truck traffic classification
VMT	vehicle miles travelled

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APPENDIX A

ADT Traffic Data of the 26 Impacted Roadways

Table 43
ADT of new asphalt pavements

ROUTE	CONTROL _SECTION	YEAR1	YEAR2	YEAR3	YEAR4	YEAR5	YEAR6	ADT1	ADT2	ADT3	ADT4	ADT5	ADT6
LA0157	082-01	2010	2007	2004	2001	1998	1995	631	258	334	331	324	213
LA0169	097-01	2015	2012	2009	2006	2003	2000	1976	2415	3000	1795	1581	1398
LA0191	432-02	2014	2008	2005	2002	1999	1996	574	687	674	652	589	815
LA0346	300-30	2014	2008	2005	2002	1999	1995	195	265	235	244	225	297
LA0005	098-03	2014	2008	2005	2002	1999	1995	1854	2865	1885	2062	1371	1437
LA0512	301-02	2014	2011	2008	2005	2002	1999	151	820	120	112	285	129
LA0513	300-04	2014	2011	2008	2005	2002	1999	725	1775	1389	1085	884	772
LA783	303-02	2014	2011	2008	2005	2002	*	337	435	374	272	296	*
LA783	303-03	2015	2012	2010	2009	2006	2003	131	196	200	200	124	93
LA789	816-09	2015	2012	2009	2006	2003	2000	1009	1414	2186	1388	1149	913

* Not available in DOTD system

Table 44
ADT of rigid/composite pavements

ROUTE	CONTROL _SECTION	YEAR1	YEAR2	YEAR3	YEAR4	YEAR5	YEAR6	ADT1	ADT2	ADT3	ADT4	ADT5	ADT6
US0171	025-07	2014	2011	2008	2005	2002	1999	10176	12113	8190	7509	7770	7560
LA0005	049-01	2014	2011	2008	2005	2002	1999	2365	5022	4056	3184	2739	2688

LA0005	049-01	2014	2011	2008	2005	2002	1999	2365	5022	4056	3184	2739	2688
LA0001	053-07	2014	2011	2008	2005	2002	1999	2675	3323	3376	2283	1870	1360
LA0005	098-02	2014	2011	2008	2005	2002	1999	4233	7926	5764	4222	4200	4024

Table 45
ADT of asphalt overlay pavements

ROUTE	CONTROL _SECTION	YEAR1	YEAR2	YEAR3	YEAR4	YEAR5	YEAR6	ADT1	ADT2	ADT3	ADT4	ADT5	ADT6
			2007	2004	2001	1998	1995	631	258	334	331	324	213
LA0154	090-04	2015	2012	2010	2009	2006	2003	789	718	899	899	986	950
LA0191	099-03	2014	2011	2008	2005	2002	1999	1087	2103	1028	933	989	811
LA0514	100-01	2014	2011	2008	2005	2002	1999	761	1118	948	815	777	838
LA3015	298-02	2014	2011	2008	2005	2002	1999	1736	2007	1667	1158	1066	835
LA0481	299-02	2014	2008	2005	2002	1999	1995	385	574	585	747	750	514
LA0512	301-02	2014	2011	2008	2005	2002	1999	151	820	120	112	285	129
LA0346	301-03	2014	2008	2005	2002	1999	1995	195	265	235	244	225	297
LA0515	302-02	2014	2011	2008	2005	2002	1999	347	217	157	180	116	141
LA0786	306-02	2014	2011	2008	2005	2002	1999	824	692	1012	241	211	285
LA0790	807-01	2015	2012	2010	2009	2006	2003	79	131	261	261	152	90
LA0789	809-07	2015	2012	2009	2006	2003	2000	1009	1414	2186	1388	1149	913
LA0788	841-02	2014	2011	2008	2005	2002	1999	405	460	430	419	405	688

APPENDIX B

Truck Factor

Determination of the overweight Truck Factor

To quantify the damage of overweight and non-overweight trucks due to the shale gas development in the Haynesville area according to the AASHTO Guide for Design of Pavement Structures [21], the truck factor of the shale-gas related trucks was an essential factor that needed to be determined. The truck factor, T_f, is the number of Equivalent single axle loads (ESALs) applied per truck and is defined as

$$T_f = (\sum_{i=1}^{n} p_i \, F_i)A \tag{20}$$

where, p_i is the percentage of total repetitions for the ith load group, F_i is the equivalent axle load factor (EALF) for the ith load group, and A is the average number of axles per truck. The permit office of Louisiana DOTD also recorded the overweight truck configurations for a large portion of permits in the database, including the axle type, axle weight, etc. In total, 119,134 permits in the Haynesville area were found with the recorded axle type and axle weight. These permits served as a good sample to determine the truck factor of the overweight trucks in the shale gas development. Table 46 summarizes the repetitions of different axle types. As indicated in Table 46, the 119,134 truck trips included 350,851 axle repetitions and this implies that the number of axles per truck, A, averages 2.95 (350,851/119,134). In addition, the quantities of these axle repetitions were categorized in terms of different axle types (i.e., load groups) as shown in Table 46.

For each axle type, the axle weight varies. Figure 37 shows the repetitions versus the axle weight. For the single, tandem, and tridem axles, the equivalent axle load factors (EALFs) for flexible pavements [21] (assuming that the pavement structure number SN is 3 and P_t is 2) were weighted according to the repetitions of the axle weight as shown in Figure 37. The weighted EALFs are summarized in Table 46. The derivation process is shown in Appendix C. For the quad-axle and five-axle trucks, the EALFs were not catalogued in the AASHTO 1993 design guide. They were estimated with the Pavement ME software using a flexible pavement structure with SN =3 in terms of equal rutting. The axle loads for quad-axle and five-axle were chosen as 80 and 100 kips respectively as indicated in Figure 37 and applied as special loads in the software. The obtained EALFs were 4.52 for quad-axle and 4.95 for five-axle. By substituting p_i, F_i, and A into equation (20), the truck factor for the overweight trucks in the Hayneville area was found to be 6.41.

Table 46
Estimation of overweight truck factor

	Single-axle	Tandem-axle	Tridem-axle	Quad-axle	Five-axle	Six-axle and other	Total	Trucks
Repetitions	113,372	98,663	93,109	24,008	21,470	229	350,851	119,134
Percentages of repetitions, p_i (%)	32	28	27	7	6	0		
EALF, F_i	0.46^a	2.77^a	2.41^a	4.52^b	4.95^b	-		
p_iF_i	0.15	0.78	0.64	0.31	0.30	0	2.18	
Truck factor, T_f								6.41

[a] Weighted EALF;

[b] Estimated by the AASHTO Pavement ME software in terms of equal rutting.

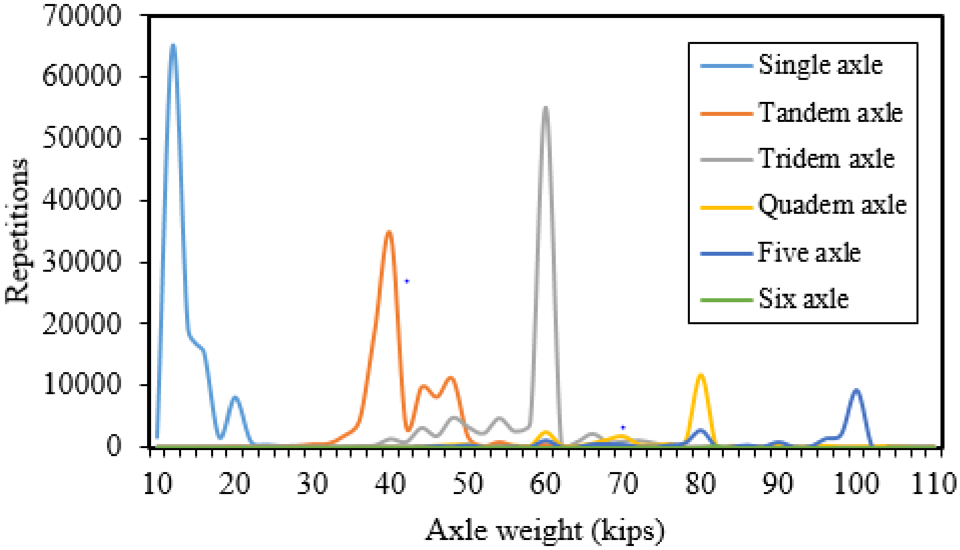


Figure 37
Repetitions of different axle types vs. axle weight

Determination of the Non-Overweight Truck Factor

For the analysis of the truck factor of a typical non-overweight truck, a three axle-set truck with the gross weight ranging from 70 to 80 kips was chosen as a representative truck, which includes a single axle (12 kips) and two tandem axles (29-34 kips). For a flexible pavement with an assumed structure number SN=3 and Pt =2, the truck factor was determined ranging from 1.32 {0.189+0.567+0.567} to 2.35 {0.189+1.08+1.08} according to the 1993 AASHTO design guide.

APPENDIX C

Weighted EALF

This section was derived based on the truck details of the 119,134 overloaded truck trips in the Haynesville area.

Table 47
Weighted EAFL for single axles

Axle Weight	Frequency	Percentage	EALF	Weighted EALF
10000	1690	1.48	0.090	0.00
12000	64995	57.33	0.189	0.11
14000	19075	16.83	0.354	0.06
16000	15602	13.76	0.613	0.08
18000	1686	1.49	1.00	0.01
20000	8151	7.19	1.56	0.11
22000	1011	0.89	2.35	0.02
24000	452	0.40	3.43	0.01
26000	253	0.22	4.88	0.01
28000	335	0.30	6.78	0.02
30000	120	0.11	9.2	0.01
32000	0	0.00	12.4	0.00
34000	0	0.00	16.3	0.00
36000	0	0.00	21.2	0.00
38000	1	0.00	27.1	0.00
40000	0	0.00	34.3	0.00
42000	0	0.00	43.0	0.00
44000	0	0.00	53.4	0.00
46000	0	0.00	65.6	0.00
More	0			
	113372	100.00		0.46

Table 48

Weighted EAFL for tandem axles

Axle Weight	Frequency	Percentage	EALF	Weighted EALF
30000	1273	1.29	0.65	0.01
32000	638	0.65	0.84	0.01
34000	1888	1.91	1.08	0.02
36000	4325	4.38	1.38	0.06
38000	19229	19.49	1.73	0.34
40000	34650	35.12	2.15	0.76
42000	3500	3.55	2.64	0.09
44000	9828	9.96	3.23	0.32
46000	8227	8.34	3.92	0.33
48000	11201	11.35	4.72	0.54
50000	1699	1.72	5.64	0.10
52000	266	0.27	6.71	0.02
54000	892	0.90	7.93	0.07
56000	259	0.26	9.30	0.02
58000	263	0.27	10.90	0.03
60000	514	0.52	12.70	0.07
62000	5	0.01	14.70	0.00
64000	0	0.00	17.00	0.00
66000	5	0.01	19.60	0.00
More	0			
	98663	100.00		2.77

Table 49
Weighted EAFL for tridem axles

Axle Weight	Frequency	Percentage	EALF	Weighted EALF
50000	16463	17.68	1.20	0.21
52000	2295	2.46	1.42	0.04
54000	4762	5.11	1.66	0.08
56000	2641	2.84	1.93	0.05
58000	3994	4.29	2.24	0.10
60000	55086	59.16	2.59	1.53
62000	550	0.59	2.98	0.02
64000	910	0.98	3.41	0.03
66000	2260	2.43	3.89	0.09
68000	911	0.98	4.43	0.04
70000	986	1.06	5.03	0.05
72000	1153	1.24	5.68	0.07
74000	713	0.77	6.41	0.05
76000	224	0.24	7.21	0.02
78000	14	0.02	8.09	0.00
80000	117	0.13	9.05	0.01
82000	0	0.00	10.10	0.00
84000	1	0.00	11.20	0.00
86000	5	0.01	12.50	0.00
More	23			
	93109	99.99		2.41

APPENDIX D

Truck Traffic Obtained from Network Level Analysis

Table 50
Overweight trips estimated by ArcGIS

Route	Control section	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
US 171	2507	909	1326	4501	4511	2185	1799	1477	882	1404	18994
La 5	4901	1004	1947	3731	4450	2357	1681	1909	1420	1262	19761
La 1	5307	1357	2207	4086	3952	1806	1674	2272	1192	858	19404
La 157	8201	113	190	245	135	132	44	143	63	26	1091
La 154	9004	326	291	674	450	257	287	222	154	107	2768
La 169	9701	983	1390	2656	2392	1765	1398	1763	1965	1235	15547
La 5	9802	1848	2757	5696	5704	3327	3380	3449	2740	1953	30854
La 5	9803	1122	2169	4525	3745	1926	1906	2016	1144	478	19031
La 5	9804	300	550	1082	987	423	390	472	204	168	4576
La 191	9903	189	385	727	570	545	349	497	325	299	3886
La 514	10001	437	411	1089	635	352	358	353	289	293	4217
La 3015	29802	245	499	852	805	475	304	371	249	151	3951
La 481	29902	7	80	55	499	161	53	30	31	42	958
La 513	30004	86	180	348	395	164	108	135	184	95	1695
La 346	30030	13	46	89	66	60	19	48	7	24	372
La 512	30102	300	703	1901	2612	889	630	862	458	382	8737
La 346	30103	35	109	242	205	185	80	87	39	84	1066
La 515	30202	134	257	671	397	199	143	218	144	146	2309
La 783	30302	6	35	30	96	8	28	54	12	10	279
La 783	30303	6	35	30	96	8	28	54	12	10	279
La 786	30602	11	119	82	215	36	35	28	41	11	578
La 191	43202	244	695	915	1024	643	426	573	438	331	5289
La 790	80701	41	37	63	35	22	12	11	6	5	232
La 789	80907	1015	1458	2751	2483	1729	1428	1723	2024	1233	15844
La 789	81609	1012	1455	2716	2477	1722	1396	1720	2024	1232	15754
La 788	84102	117	190	347	264	119	91	47	33	164	1372

Table 51
Overweight trips due to shale gas activities estimated by ArcGIS

Route	Control section	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
US 171	2507	153	505	2948	3036	841	622	589	212	125	9032
La 5	4901	169	742	2444	2995	907	582	762	341	112	9053
La 1	5307	228	841	2676	2660	695	579	907	286	76	8948
La 157	8201	19	72	160	91	51	15	57	15	2	483
La 154	9004	55	111	441	303	99	99	89	37	10	1243
La 169	9701	165	530	1740	1610	680	484	703	472	110	6492
La 5	9802	310	1050	3731	3839	1281	1169	1376	658	174	13588
La 5	9803	188	826	2964	2520	742	659	804	275	43	9022
La 5	9804	50	210	709	664	163	135	188	49	15	2183
La 191	9903	32	147	476	384	210	121	198	78	27	1672
La 514	10001	73	157	713	427	136	124	141	69	26	1866
La 3015	29802	41	190	558	542	183	105	148	60	13	1840
La 481	29902	1	30	36	336	62	18	12	7	4	507
La 513	30004	14	69	228	266	63	37	54	44	8	784
La 346	30030	2	18	58	44	23	7	19	2	2	175
La 512	30102	50	268	1245	1758	342	218	344	110	34	4369
La 346	30103	6	42	159	138	71	28	35	9	7	494
La 515	30202	23	98	440	267	77	49	87	35	13	1088
La 783	30302	1	13	20	65	3	10	22	3	1	137
La 783	30303	1	13	20	65	3	10	22	3	1	137
La 786	30602	2	45	54	145	14	12	11	10	1	294
La 191	43202	41	265	599	689	248	147	229	105	29	2352
La 790	80701	7	14	41	24	8	4	4	1	0	105
La 789	80907	171	555	1802	1671	666	494	687	486	110	6642
La 789	81609	170	554	1779	1667	663	483	686	486	110	6598
La 788	84102	20	72	227	178	46	31	19	8	15	616

APPENDIX E

TTC Group 1 Truck Loads

Table 52
Normalized Single axle load distribution factors for TTC Group 1

In Lbs	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
3000	3.19	6.18	23.26	14.85	16.32	0.65	1.23	0.2	0.59	7.31
4000	2.13	13.09	17.65	13.2	12.3	0.95	1.74	0.33	0.59	6.24
5000	3.19	17.59	8.51	6.27	10.27	2.48	2.17	0.57	0.98	3.23
6000	7.7	21.59	4.48	1.65	9.9	3.31	3.18	1.43	3.35	4.73
7000	10.73	11.56	2.85	1.98	6.82	3.51	2.68	3.79	4.33	2.58
8000	18.84	8.87	5.02	0.99	6.77	12.29	8.32	6.35	9.94	4.52
9000	14.58	4.37	4.66	0.66	4.73	11.59	12	5.3	8.46	4.73
10000	15.48	4.51	7.6	3.96	6.32	18.85	20.17	10.67	14.86	7.53
11000	6.96	2.58	6.56	3.63	4.67	19.63	20.32	10.75	11.52	9.03
12000	5.73	2.53	6.33	10.89	5.75	17.89	15.04	9.69	10.63	12.69
13000	3.03	1.59	3.76	10.56	3.45	5.92	6.94	8.39	11.32	6.45
14000	3.77	1.53	2.67	11.88	3.25	2.31	4.34	10.51	9.55	6.88
15000	2.21	1.09	1.76	6.27	2.2	0.43	1.08	10.43	6.59	4.09
16000	0.74	0.64	1.04	6.6	1.6	0.12	0.22	7.13	2.95	4.95
17000	1.31	0.78	1.45	3.63	1.77	0.03	0.14	6.84	2.76	3.23
18000	0.16	0.48	0.68	0.99	1.02	0.01	0.14	3.14	0.59	3.23
19000	0.16	0.39	0.9	0.66	1.09	0.02	0.22	2.73	0.79	2.15
20000	0	0.18	0.36	0.33	0.57	0	0	0.69	0.1	1.51
21000	0	0.27	0.23	0	0.42	0	0	0.37	0.1	1.51
22000	0	0.07	0.14	0	0.3	0	0	0.33	0	0.65
23000	0	0.04	0.05	0.33	0.21	0	0	0.24	0	0.86
24000	0	0	0	0	0.1	0	0	0.12	0	0.65
25000	0	0.02	0.05	0.33	0.05	0	0	0	0	0
26000	0	0	0	0	0.03	0	0	0	0	0.43
27000	0	0.01	0	0	0.03	0	0.07	0	0	0
28000	0	0.02	0	0.33	0.02	0	0	0	0	0
29000	0	0	0	0	0.02	0	0	0	0	0.43
30000	0	0	0	0	0.01	0	0	0	0	0
31000	0	0	0	0	0	0	0	0	0	0.22
32000	0	0	0	0	0.01	0	0	0	0	0.22
33000	0	0	0	0	0	0	0	0	0	0
34000	0	0	0	0	0	0	0	0	0	0
35000	0	0	0	0	0	0	0	0	0	0

36000	0	0	0	0	0	0	0	0	0	0
37000	0.08	0	0	0	0	0	0	0	0	0

Table 53
Normalized Tandem axle load distribution factors for TTC Group 1

6000	15.61	0	57.91	0	0	8.17	14.36	0	4.75	28.68
8000	7.02	0	7.13	0	0	9.83	6.21	0	10.74	8.44
10000	12.15	0	7.87	0	0	12.33	8.84	0	21.48	11.5
12000	16.33	0	7.01	0	0	15.94	10.08	0	22.71	16.41
14000	16.95	0	8.09	0	0	16.73	12.36	0	22.01	9.51
16000	13.55	0	6.02	0	0	15.85	15.29	0	12.15	6.9
18000	8.86	0	3.08	0	0	14.36	17.09	0	3.87	7.82
20000	5.85	0	1.57	0	0	4.91	9.08	0	2.29	4.29
22000	1.67	0	0.75	0	0	1.37	3.76	0	0	3.68
24000	0.89	0	0.3	0	0	0.34	1.73	0	0	1.23
26000	0.78	0	0.22	0	0	0.11	0.69	0	0	0.61
28000	0.17	0	0.02	0	0	0.04	0.28	0	0	0.15
30000	0.17	0	0	0	0	0.01	0.07	0	0	0.61
32000	0	0	0	0	0	0.01	0.07	0	0	0
34000	0	0	0	0	0	0	0.07	0	0	0.15
36000	0	0	0.02	0	0	0	0	0	0	0
38000	0	0	0	0	0	0	0.03	0	0	0
40000	0	0	0	0	0	0	0	0	0	0
42000	0	0	0	0	0	0	0	0	0	0
44000	0	0	0	0	0	0	0	0	0	0
46000	0	0	0	0	0	0	0	0	0	0
48000	0	0	0	0	0	0	0	0	0	0
50000	0	0	0	0	0	0	0	0	0	0
52000	0	0	0	0	0	0	0	0	0	0
54000	0	0	0	0	0	0	0	0	0	0
56000	0	0	0	0	0	0	0	0	0	0
58000	0	0	0	0	0	0	0	0	0	0
60000	0	0	0	0	0	0	0	0	0	0
62000	0	0	0	0	0	0	0	0	0	0
64000	0	0	0	0	0	0	0	0	0	0
66000	0	0	0	0	0	0	0	0	0	0
68000	0	0	0	0	0	0	0	0	0	0
70000	0	0	0	0	0	0	0	0	0	0
72000	0	0	0	0	0	0	0	0	0	0
74000	0	0	0.02	0	0	0	0	0	0	0

Table 54
Normalized Tridem axle load distribution factors for TTC Group 1

In Lbs	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
12000	0	0	0	55.59	0	0	57.27	0	0	0
15000	0	0	0	19.74	0	0	17.11	0	0	0
18000	0	0	0	17.87	0	0	14.97	0	0	0
21000	0	0	0	5.15	0	0	8.11	0	0	0
24000	0	0	0	0.55	0	0	1.99	0	0	0
27000	0	0	0	0.44	0	0	0.43	0	0	0
30000	0	0	0	0.11	0	0	0.1	0	0	0
33000	0	0	0	0.44	0	0	0.03	0	0	0
36000	0	0	0	0.11	0	0	0	0	0	0
39000	0	0	0	0	0	0	0	0	0	0
42000	0	0	0	0	0	0	0	0	0	0
45000	0	0	0	0	0	0	0	0	0	0
48000	0	0	0	0	0	0	0	0	0	0
51000	0	0	0	0	0	0	0	0	0	0
54000	0	0	0	0	0	0	0	0	0	0
57000	0	0	0	0	0	0	0	0	0	0
60000	0	0	0	0	0	0	0	0	0	0
63000	0	0	0	0	0	0	0	0	0	0
66000	0	0	0	0	0	0	0	0	0	0
69000	0	0	0	0	0	0	0	0	0	0
72000	0	0	0	0	0	0	0	0	0	0
75000	0	0	0	0	0	0	0	0	0	0
78000	0	0	0	0	0	0	0	0	0	0
81000	0	0	0	0	0	0	0	0	0	0
84000	0	0	0	0	0	0	0	0	0	0
87000	0	0	0	0	0	0	0	0	0	0
90000	0	0	0	0	0	0	0	0	0	0
93000	0	0	0	0	0	0	0	0	0	0
96000	0	0	0	0	0	0	0	0	0	0
99000	0	0	0	0	0	0	0	0	0	0
102000	0	0	0	0	0	0	0	0	0	0

APPENDIX F

DOTD Overweight Truck Fee Regulation

Table 55
First overweight permit fee schedule from DOTD

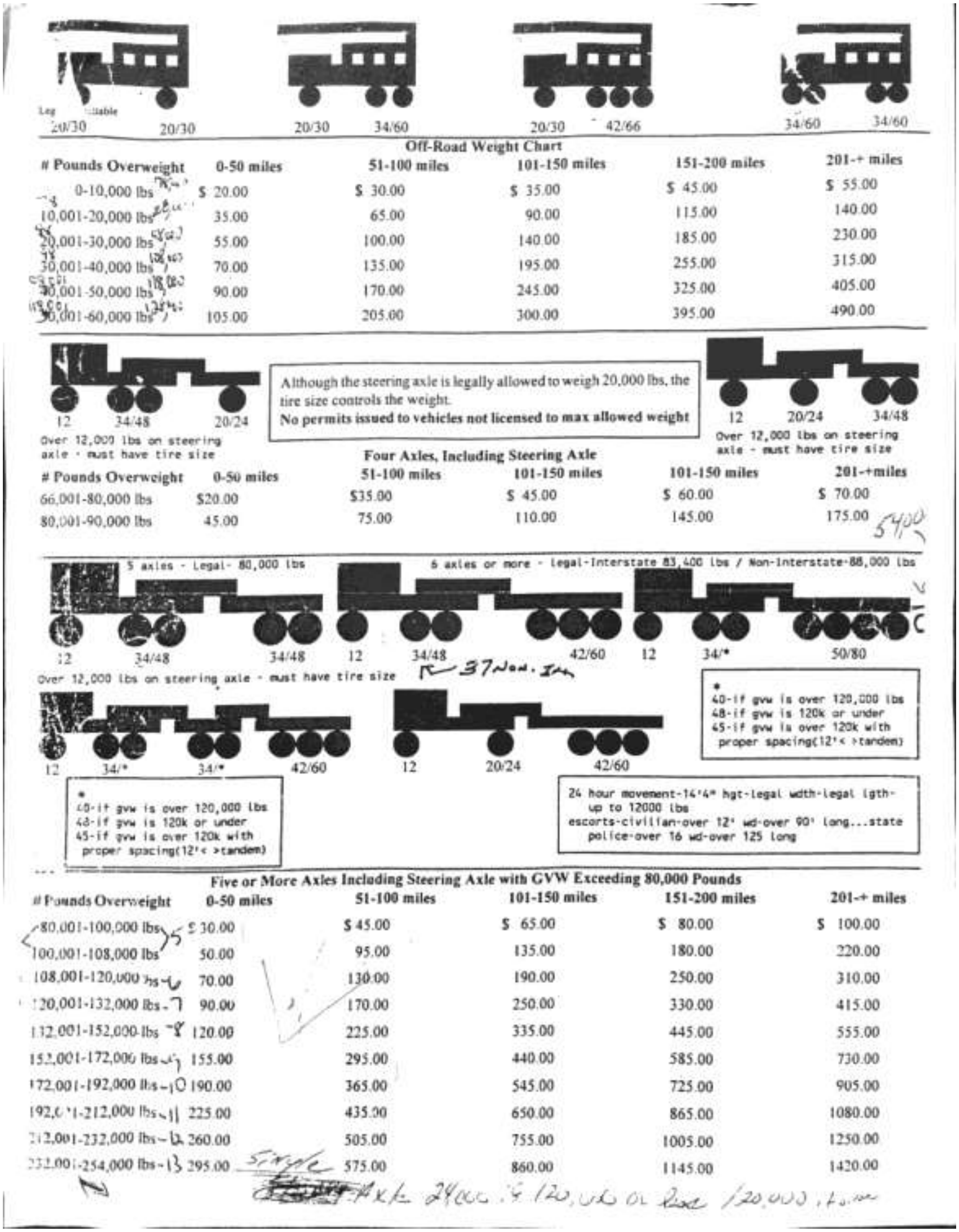
FIRST OVERWEIGHT PERMIT FEE SCHEDULE					
This schedule is for three types of vehicles: • Vehicles and combinations of vehicles which do not exceed their legal gross weight, but do exceed the legal axle weight on one to three axles or axle groups* (including steering axles). • Vehicles or combinations of vehicles which have two or three axles**total and which exceed both their legal gross weight and legal axle weight. • All two-to-four axle** off-road equipment.					
EXCESS WEIGHT (in pounds)	DISTANCE (in miles)				
	0-50	51-100	101-150	151-200	Over 200
0-10,000	$20.00	$30.00	$35.00	$45.00	$55.00
10,001-20,000	35.00	65.00	90.00	115.00	140.00
20,001-30,000	55.00	100.00	140.00	185.00	230.00
30,001-40,000	70.00	135.00	195.00	255.00	315.00
40,001-50,000	90.00	170.00	245.00	325.00	405.00
50,001-60,000	105.00	205.00	300.00	395.00	490.00
Over 60,000	$10.00 plus $0.07 per ton-mile				
* Axle groups are tandem, tridum, and quadrum axles. ** “Axle” here refers to single or individual axles. Tandem groups will be counted as two axles and tridum axle groups as three axles.					

Table 56
Second overweight permit fee schedule from DOTD

SECOND OVERWEIGHT PERMIT FEE SCHEDULE					
This schedule is for combinations of vehicles with four axles* (including the steering axle).					
GROSS WEIGHT (in pounds)	DISTANCE (in miles)				
	0-50	51-100	101-150	151-200	Over 200
66,001-80,000	$20.00	$35.00	$45.00	$60.00	$70.00
80,001-90,000	45.00	75.00	110.00	145.00	175.00
*“Axle” here refers to single or individual axles. Tandem axle groups will be counted as two axles and tridum axle groups as three axles.					

Table 57
Third overweight permit fee schedule from DOTD

THIRD OVERWEIGHT PERMIT FEE SCHEDULE					
This schedule is for combinations of vehicles with five or more axles* (including the steering axle) when the gross weight exceeds 80,000 pounds.					
GROSS WEIGHT (in pounds)	DISTANCE (in miles)				
	0-50	51-100	101-150	151-200	Over 200
80,000-100,000	$30.00	$45.00	$65.00	$80.00	$100.00
100,001-108,000	50.00	95.00	135.00	180.00	220.00
108,001-120,000	70.00	130.00	190.00	250.00	310.00
120,001-132,000	90.00	170.00	250.00	330.00	415.00
132,001-152,000	120.00	225.00	335.00	445.00	555.00
152,001-172,000	155.00	295.00	440.00	585.00	730.00
172,001-192,000	190.00	365.00	545.00	725.00	905.00
192,001-212,000	225.00	435.00	650.00	865.00	1080.00
212,001-232,000	260.00	505.00	755.00	1005.00	1250.00
232,001-254,000	295.00	575.00	860.00	1145.00	1420.00
Over 254,000	$10.00 - plus $0.50 per ton-mile in excess of 80,000 pounds, plus a fee for structural evaluation based on the following schedule: $125.00 – for evaluation of treated timber, concrete slab, and precast concrete slab bridges. $850.00 – for evaluation of truss, continuous span and movable bridges and for all Mississippi River structures. $500.00 – for all other structures.				
* “Axle” here refers to single or individual axles. Tandem axle groups will be counted as two axles and tridum axle groups as three axles.					



Leg lable

20/30 20/30

20/30 34/60

20/30 42/66

34/60 34/60

Off-Road Weight Chart

# Pounds Overweight	0-50 miles	51-100 miles	101-150 miles	151-200 miles	201-+ miles
0-10,000 lbs	$ 20.00	$ 30.00	$ 35.00	$ 45.00	$ 55.00
10,001-20,000 lbs	35.00	65.00	90.00	115.00	140.00
20,001-30,000 lbs	55.00	100.00	140.00	185.00	230.00
30,001-40,000 lbs	70.00	135.00	195.00	255.00	315.00
40,001-50,000 lbs	90.00	170.00	245.00	325.00	405.00
50,001-60,000 lbs	105.00	205.00	300.00	395.00	490.00

12 34/48 20/24

Over 12,000 lbs on steering axle - must have tire size

Although the steering axle is legally allowed to weigh 20,000 lbs, the tire size controls the weight.

No permits issued to vehicles not licensed to max allowed weight

12 20/24 34/48

Over 12,000 lbs on steering axle - must have tire size

Four Axles, Including Steering Axle

# Pounds Overweight	0-50 miles	51-100 miles	101-150 miles	101-150 miles	201-+miles
66,001-80,000 lbs	$20.00	$35.00	$ 45.00	$ 60.00	$ 70.00
80,001-90,000 lbs	45.00	75.00	110.00	145.00	175.00

5400

5 axles - Legal- 80,000 lbs

6 axles or more - Legal-Interstate 83,400 lbs / Non-Interstate-88,000 lbs

12 34/48 34/48

12 34/48 42/60 ← 37 Non. Int.

12 34/* 50/80

Over 12,000 lbs on steering axle - must have tire size

*
40-if gvw is over 120,000 lbs
48-if gvw is 120k or under
45-if gvw is over 120k with
proper spacing(12'< >tandem)

12 34/* 34/* 42/60

12 20/24 42/60

*
40-if gvw is over 120,000 lbs
48-if gvw is 120k or under
45-if gvw is over 120k with
proper spacing(12'< >tandem)

24 hour movement-14'4" hgt-legal wdth-legal lgth-
up to 12000 lbs
escorts-civilian-over 12' wd-over 90' long...state
police-over 16 wd-over 125 long

Five or More Axles Including Steering Axle with GVW Exceeding 80,000 Pounds

# Pounds Overweight	0-50 miles	51-100 miles	101-150 miles	151-200 miles	201-+ miles
80,001-100,000 lbs 5	$ 30.00	$ 45.00	$ 65.00	$ 80.00	$ 100.00
100,001-108,000 lbs	50.00	95.00	135.00	180.00	220.00
108,001-120,000 lbs - 6	70.00	130.00	190.00	250.00	310.00
120,001-132,000 lbs - 7	90.00	170.00	250.00	330.00	415.00
132,001-152,000 lbs - 8	120.00	225.00	335.00	445.00	555.00
152,001-172,000 lbs - 9	155.00	295.00	440.00	585.00	730.00
172,001-192,000 lbs - 10	190.00	365.00	545.00	725.00	905.00
192,001-212,000 lbs - 11	225.00	435.00	650.00	865.00	1080.00
212,001-232,000 lbs - 12	260.00	505.00	755.00	1005.00	1250.00
232,001-254,000 lbs - 13	295.00	575.00	860.00	1145.00	1420.00

Single Axle 24000 & 120,000 or less /20,000 [illegible]

Figure 38
DOTD regulation about axle groups

APPENDIX G

Inputs For Overweight Equipment

Table 58
Typical overweight trucks for shale gas development with various gross weight

Type	Make & Model		Axle configuration	GVW/ Axle weight combination (kips)
1. Drilling/ Workover Rigs	ZJ 30 Truck-Mounted Drilling Rig		sin+tan+tan+quad	180.4/12+46+46+76
	ZJ 10/900CZ Truck Mounted Drilling Rig		sin+tan+tri	110/12+44+55
	XJ Truck Mounted Workover Rig	XJ 350	sin+tan+tan	92.4/12+40+40
		XJ 150	sin+tan+tan+quad	167.2/12+39+39+78
		XJ 120	sin+tri+tri	121/12+55+55
		XJ 100	sin+tan+tri	116.6/12+44+60
		XJ 80	sin+tan+tri	113.3/12+42+60
		XJ 60	sin+tan+tri	112.2/12+42+58
		XJ 40	sin+tan+tan	83.6/12+36+36
		XJ 550	sin+tan+tri	118.8/12+46+60
2. Fracturing Units	YLC140-5600 Truck Mounted Fracturing Unit		tan+tan	81.8/41+41
	ACEWEL 2500 Truck-mounted Fracturing Pump		sin+tan+tan	99/12+44+44
	YLC105-2250 Truck Mounted Fracturing Unit		tan+tan	83.8/42+42
3. Coiled Tube Units	SERVA Coiled Tube Units 0.175 Tube Wall 0.156 Tube Wall 0.134 Tube Wall		sin+quad+quad sin+quad+quad sin+quad+quad	170.8/12+80+80 164.0/12+76+76 156.0/12+72+72
	Jereh LGT450 Trailer Mounted Coiled Tubing Unit		sin+tan+quad	120/12+40+68
4. Nitrogen Pumper	Weber trailer mounted 180K N2 pumper		sin+tan+tan	85/12+36+36
	PENT-640 K truck mounted direct-fired nitrogen unit		tan+tan	88.2/44+44
5. Equipment Transported with Truck	Case 470B excavator		sin+tan+quad	135.8/12+46+78
	Case CX490D excavator		sin+tri+quad	141.3/12+56+74
	Caterpillar 349F XE excavator		sin+tri+quad	145.6/12+58+76
	AF 190/ AF 180D Drilling rig		sin+tri+quad	151/12+60+80
	AF 12 Drilling Rig		sin+tan+quad	129/12+44+74

* Axle configuration in the figures may be adjusted to comply with DOTD regulations

** sin-single axle; tan-tandem axle; tri-tridem axle; quad-quad axle

(a)

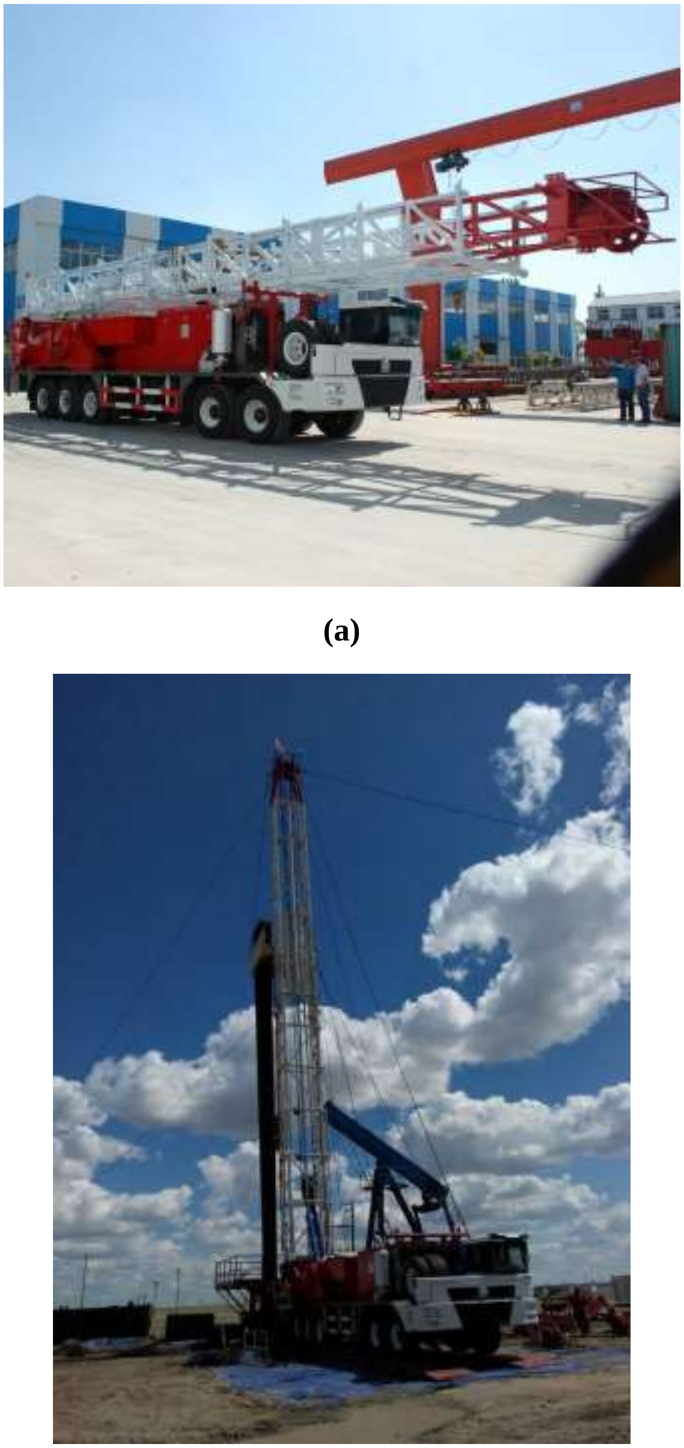
(b)

Figure 39
ZJ 30 truck-mounted drilling rig

Figure 40
ZJ 10/900CZ truck mounted drilling rig

Figure 41
XJ 350 truck mounted workover rig

Figure 42
XJ 550 truck mounted workover rig



(a)

(b)

Figure 43

XJ 550 truck mounted workover rig

Figure 44
YLC140-5600 truck mounted fracturing unit

Figure 45
ACEWEL 2500 truck-mounted fracturing pump

Figure 46
YLC105-2250 truck mounted fracturing unit

Figure 47
SERVA coiled tube units

(a)

(b)

Figure 48
Jereh LGT450 trailer mounted coiled tubing unit

Figure 49
Weber trailer mounted 180K N2 pumper

(a) **(b)**

Figure 50
PENT-640 K truck mounted direct-fired nitrogen unit

Figure 51
Case CX470B excavator

Figure 52
Case CX490D excavator

Figure 53
Caterpillar 349F XE excavator

Figure 54
AF 190/ AF 180D drilling rig

Figure 55
AF 12 drilling rig

APPENDIX H

Overweight Truck Fee for Gross Truck Weight Ranges

Table 59
Permit fee about truck gross weights on LA roadway (AADT≥2000)*

Truck Gross Weight (lbs.)	Distance (miles)				
	0-50	51-100	101-150	151-200	Over 200
80,000-100,000	$326.72	$490.08	$707.895	$871.255	$1089.07
100,001-108,000	361.37	686.61	975.71	1300.94	1590.04
108,001-120,000	388.35	721.22	1054.10	1386.97	1719.84
120,001-132,000	423.40	799.75	1176.10	1552.45	1952.33
132,001-152,000	475.09	890.80	1326.30	1761.80	2197.30
152,001-172,000	548.68	1044.26	1557.53	2070.81	2584.09
172,001-192,000	633.66	1217.29	1817.60	2417.90	3018.21
192,001-212,000	731.80	1414.82	2114.09	2813.37	3512.64
212,001-232,000	845.15	1641.53	2454.17	3266.81	4063.20
232,001-254,000	976.05	1902.46	2845.42	3788.38	4698.25

* Based on Table 39 and the relationship in Table 20

Table 60
Permit fee about truck gross weights on US Highway *

Truck Gross Weight (lbs.)	Distance (miles)				
	0-50	51-100	101-150	151-200	Over 200
80,000-100,000	$64.45	$96.68	$139.65	$171.88	$214.85
100,001-108,000	71.29	135.45	192.49	256.65	313.68
108,001-120,000	76.61	142.28	207.95	273.62	339.29
120,001-132,000	83.53	157.77	232.02	306.27	385.15
132,001-152,000	93.73	175.74	261.65	347.57	433.48
152,001-172,000	108.24	206.01	307.27	408.53	509.79
172,001-192,000	125.01	240.15	358.57	477.00	595.43
192,001-212,000	144.37	279.11	417.07	555.02	692.97
212,001-232,000	166.73	323.84	484.16	644.47	801.58
232,001-254,000	192.55	375.32	561.34	747.37	926.86

* Based on Table 39 and the relationship in Table 20

Table 61
Permit fee about truck gross weights on Interstate Highways*

Truck Gross Weight (lbs.)	Distance (miles)				
	0-50	51-100	101-150	151-200	Over 200
80,000-100,000	$32.23	$48.34	$69.83	$85.94	$107.43
100,001-108,000	35.65	67.73	96.24	128.32	156.84
108,001-120,000	38.31	71.14	103.98	136.81	169.64
120,001-132,000	41.76	78.89	116.01	153.13	192.58
132,001-152,000	46.86	87.87	130.83	173.78	216.74
152,001-172,000	54.12	103.00	153.63	204.26	254.89
172,001-192,000	62.50	120.07	179.29	238.50	297.71
192,001-212,000	72.18	139.56	208.53	277.51	346.48
212,001-232,000	83.36	161.92	242.08	322.24	400.79
232,001-254,000	96.28	187.66	280.67	373.68	463.43

* Based on Table 39 and the relationship in Table 20