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Truck impact on buried water pipes in interdependent water and road infrastructures

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Abstract: In the development of sustainable and resilient infrastructures to adapt to the rapidly changing natural and social environments, the complexity of dependencies and interdependencies within critical infrastructure systems needs to be fully understood as they affect various components of risk and lead to cascading failures. Water and road infrastructures are highly co-located but often managed and maintained separately. One important aspect of their interdependencies is the impact of vehicle load on a road on an underlying water pipe. Existing studies lack a comprehensive evaluation of this subject that would consider possible critical failure scenarios. This study constructed finite element models to analyze the responses of buried water pipes to vehicle loads under an array of scenarios, including various loads, pipe materials, pipe dimensions, and possible extreme conditions such as corrosion in pipes and sinkhole under the pipe. Results showed negligible impact of heavy trucks on buried water pipes. Pipe deflection under a maximum allowable truck load in the worst condition is still within the allowable range specified in standards such as those from the American Water Works Association. This implies that the impact of heavy vehicles on water pipes may not need to be considered in the context of interdependency between water and road infrastructure, which leads to a more unidirectional dependency between these two infrastructures in this regard.

Keywords: infrastructure interdependency, truck load, water infrastructure, transportation infrastructure

1. Introduction

The ever-growing reliance of our society on infrastructure systems and the increasing number of correlated or cascading failures in these systems due to man-made incidents or natural disasters have posed new challenges to the construction and management of infrastructure systems. With research expanding in infrastructure construction and management with risk considerations [1–3], the necessity of exploring the interdependencies among infrastructure systems is also increasing [4]. Among many infrastructure interdependencies, the relationship between water pipe and road has been noticeably less explored. These two critical civil infrastructure systems are predominantly geographically co-located, particularly in urban areas, in that water pipes are buried underneath road pavements. The operation and maintenance of the two network systems, however, are generally independent from each other in the current practices of many agencies.

The interdependency between the road and water infrastructures may be understood from several perspectives: physical or structural interactions, operational influences, and maintenance and repair/replacement scheduling due to shared labor, budget, and equipment resources.

From the structural interaction perspective, on one hand, water pipe may impact the road structure through undermining its foundation support when the water pipe breaks and leaks. Consequently, the traffic flow on the road may be seriously disrupted. Cases of this type of failure have been frequently reported in the news and literatures [5,6]. On the other hand, the impact of road on the structural performance of water pipe has been less noticed and reported. Understanding this type of impact may help us determine whether the structural interdependency between water pipe and road is unidirectional or bidirectional. In some literature, the unidirectional effect is treated simply as "dependency" whereas interdependency refers to the bidirectional effects [7,8]. Clarifying the nature of such interdependency is necessary for further analysis and modeling of the coupled systems towards more rational operational and maintenance policies. For example, in using graph theory to analyze interdependent infrastructure networks, a decision must be made on whether one or two directional links should be used to model impact propagation between the networks.

Structurally, a water pipe, especially a water supply pipe, needs to carry hydraulic pressure. For water pipes buried below roadways, they are also subjected to geostatic and traffic loads. These factors are considered in the current practices of water pipe design to provide a required carrying capacity (i.e., pipe diameter) and to determine the depth of cover and thickness of pipe wall along with other design parameters. Loads coming from hydrostatic pressure as well as standard vehicles are used in the design [9]. On many occasions, however, the minimum depth of cover may not be maintained due to poor quality control and management during installation. It is also likely that some actual vehicle loads would exceed the standard design loads in the field due to vehicle overloading or traffic pattern change (e.g., traffic diversion in emergency). For example, in the U.S., standard HS-20 truck loads (320 kN total truck weight distributed on three axles as 35.5, 142, and 142 kN, respectively) are considered in the design of steel pipes [9], but the U.S. federal and many state limits for trucks on roads are 356 kN gross vehicle weight, 89 kN on a single axle, and 151 kN on a tandem axle group [10]. In addition, when the pipe deteriorates structurally (e.g. due to corrosion) and/or is subjected to unexpected and unfavorable events (e.g., loss of soil support or sinkhole formation), it becomes more vulnerable to the external loading. For pipes located under roadways, replacing or repairing damaged or failed sections is difficult and interruptive to the ground traffic. It is, therefore, very important that the water pipes are mechanically sound throughout their service life. In this regard, the impact of traffic load on the buried pipes needs to be clearly understood.

2. Literature Review and Objectives

There have been some prior works in the literature that studied the vehicle load effect on buried water pipes, pipes that serve other utilities such as gas transmission, or other underground structures such as culverts. Alzabeebee et al. [11] summarized several studies that investigated differences in the effect of moving and static traffic loads on buried infrastructures (pipes, culverts etc.). In those studies, some conducted on-site experiments, some performed numerical simulation [12–15], and some adopted both approaches [16].

Table 1 lists a number of published works on the analysis of the buried pipe facilities subjected to traffic or external loads. As can be seen, it covers a number of topics including the effect of backfill height and loading condition on pipes [12,15], impact factors for dynamic loading [13], performance of culvert joints in response to traffic loading [14], effect of pavement structure on the structural response of box culvert subjected to traffic load [15], and minimum soil cover for High Density Poly Ethylene (HDPE) corrugated pipe [16]. A few studies have also dedicated their efforts to understanding the behavior and design consideration of buried pipes under traffic loads.

Table 1. A summary of the studies on buried facilities subjected to traffic or external loading.

Source	Objective	Infrastructure type	Analysis type	Considered materials	Considered dimensions	Considered max loading
[12]	Performance observation of in-service culverts	Corrugated steel culvert	On site experiment	Corrugated steel	Span ranging from 3.2 to 7.0 m	HS 20-44 (280 kN), transverse loading
[13]	Estimating impact factors for culvert design	Corrugated steel culvert	On site experiment	Corrugated steel	Span ranging from 4.6 to 12.4 m	280 kN, transverse loading
[14]	Investigating effect of pipe joints under traffic load	Culvert	On site	HDPE, Corrugated metal, Reinforced concrete	Diameter ranging from 0.9 to 2.1 m	192 kN and 203 kN, transverse loading
[15]	Observing structural responses	Box culvert	On site	Reinforced concrete	~4 m span	105 kN, transverse loading
[16]	Determining minimum cover height of corrugated plastic pipe	Culvert	On site data collection and design solution using computer program	HDPE	Diameter ranging from 0.3 to 0.9 m	H trucks, max H-30 truck
[17]	Observing buried pipe behavior under live loads	Corrugated metal pipe and circular plastic pipe	Field test and finite element (FE) modeling	HDPE, PVC, Steel, Aluminum	Nominal diameter 0.9 and 1.2 m	142 kN axle load, transverse loading
[18]	Evaluating the minimum cover required for safe use of thermoplastic pipes	Circular pipe	FE modeling with nonlinear soil model	HDPE, PVC	Diameter 0.3, 0.9, 1.5 M	H25 (223 kN), transverse loading
[19,20]	Evaluating the short-term field performance of buried flexible pipe	Corrugated pipes	Field test and FE analysis	HDPE, PVC, Metal pipes	Diameter 0.9 and 1.2 m	HS 20 (178 kN), transverse loading
[11]	Comparing the effect of static and moving loads	Corrugated metal pipe	FE analysis	Flexible metal pipe	1.2 m diameter, 0.08 m thickness	192 kN moving load, transverse loading

Following observations can be made concerning the current state of literature dealing with the behavior of buried pipes under external vehicle loading:

- Most of the experimental studies considered standard vehicle loads that are used in conventional design methods for infrastructure. For example, the HS-20 truck loading or other form of loading with similar or lower loads has been used by most studies listed in Table 1. According to the recent statistics reported in [21], however, there is appreciable truck traffic above the 356 kN federal gross vehicle weight limit on both Interstate and non-Interstate roads in the U.S. Edgar et al. [22] performed a numerical study that evaluated the effect of a super heavy truck, weighing 8,900 kN distributed on 19 axles (each axle load around 445 kN) and found that the maximum pipe deflection under the super heavy truck loading was less than 2% of the pipe diameter. Their paper, however, did not describe the details of analysis such as the orientation of the loading and the axle spacings and did not consider the deteriorated condition of the pipe or foundation support.

- A range of standard pipe materials and dimensions in terms of diameter and thickness are currently used in the pipe design practice. Although some studies have investigated variations in the responses of buried pipes under vehicle loads for a range of pipe dimensions or for other properties related to pipe dimensions such as pipe stiffness, a thorough study on how the response of a buried pipe varies along with the range of standard pipe dimensions is still absent in the literature. To answer the question whether pipes are affected by truck overloads, various states of the practice pipe dimension and materials need to be considered. The current state of the literature partly lacks in this aspect.
- When it comes to the question of whether the buried pipe infrastructure is affected by the vehicular (especially heavy trucks) movement, it is very difficult to reach a conclusion from the existing research that deals with the buried pipe behavior under vehicle loads. There are existing industry standards on pipe design methods, standard pipe diameters, and standard depths of cover for use in various field conditions, but critical condition may arise when a few of these regulations are not implemented, pipe strength deteriorates below expectation, or the loading situation is way beyond the expected level.

In summary, full understanding of the interdependencies between the two critical infrastructures (water and road) still lacks deserved attention in the existing literature. A starting point to address this issue is to unravel the physical interdependencies that may arise from the interaction of the infrastructures in operation.

For the above reasons, this study intends to investigate whether currently operational water transmission and distribution pipes can withstand the vehicle loads heavier than the standard design truck load under various conditions. Specifically, the research objectives include:

1. Determine the variation of pipe behavior within the spectrum of standard pipe materials and dimensions as per current state of practice.
2. Investigate pipe responses under various loading scenarios, including orientation of vehicle chassis and combinations of multiple axle loads of a truck.
3. Understand pipe responses to vehicle loading under anomaly conditions or unexpected situations. Currently, a large portion of the operational pipes have aged considerably and hence corroded [23,24]. Also, a frequently reported phenomenon in the news is pipe break and sinkhole or void formation below the pipe [25,26]. Hence, these factors will be considered in our analysis.

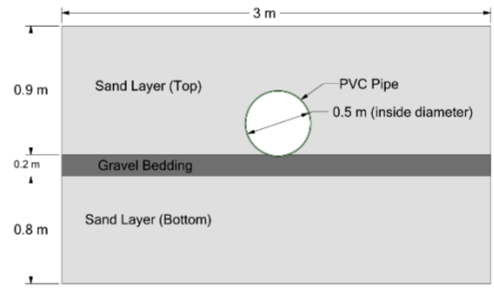
The remainder of this paper is organized as follows. Section 3 builds and validates an FE model for a buried pipe under a vertical load. Section 4 analyzes the pipe responses for various scenarios with an experimental FE model. Section 5 discusses analysis results and summarize conclusions.

3. Validation of FE Model for Buried Pipe under Vertical Load

A finite element (FE) modeling and analysis approach is adopted in this study, which includes construction of a typical model of a buried pipe subjected to external loading, model validation with laboratory test data, and numerical experiments using the calibrated parameters from the validation model.

This section describes the construction of a validation FE model based on a laboratory experiment reported in the literature for the behavior of a buried pipe under an external load. Component behavior and parameter values of the validation model were determined based on a close match between the predicted and recorded pipe responses, and then used to construct the experimental model for further analysis.

The laboratory experiment was taken from a previous study by Edgar et al. [22]. In their study, a container box (referred to as soil box) with a circular hole drilled on each of two opposite side faces, as shown in Figure 1, was used to measure the pipe behavior under external loading. Pipes of different materials were inserted through the two holes for different experiments. The soil box was filled with compacted layers of granular materials. The sides of the box were reinforced with I-beams to prevent bulging of the box due to the weight of the soil. After inserting the pipe and filling the box with soil layers, a static load was applied at the center of the top surface above the pipe. Strain gauges and linear variable differential transformers (LVDTs) were instrumented on the pipe to measure its strains and deformations, respectively. In the experiment, a 107 kN static load was applied gradually and a maximum vertical displacement of the pipe crown was measured at 2.8 mm.



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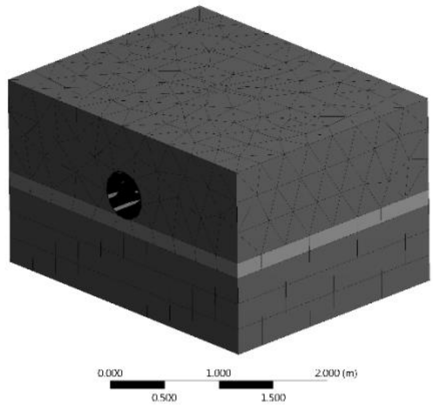


(**b**)

Figure 1. Illustration of the soil box experimental setup: (a) Orientation of granular layers and pipe, (b) 3D FE model in ANSYS 19.1 [22].

In this study, an FE model was constructed in the FE software ANSYS Workbench 19.1, as shown in Figure 1(b), to represent the experiment setup and mimic the behaviors of different components of the soil box when an unjointed PVC pipe was inserted. Geometric and material information of the test setup was extracted from the reference paper with reasonable assumptions. For example, while the depth of cover of the PVC pipe was given in the reference, the thickness of different soil layers was partially reported. It was mentioned that clear sand was used to create a 0.4 m depth of cover in the top layer. The thickness of the top soil layer, therefore, can be reasonably derived as 0.9 m, which is the depth of cover plus the diameter of the pipe (0.5 m). The thickness of the gravel layer (0.2 m) was given in the reference. The thickness of the bottom sand layer was assumed to be 0.8 m based on the provided diagram where the bottom layer is slightly thinner than the top layer [22]. While the soil parameters were given, properties of the pipe material were not reported except its material type (polyvinyl chloride, PVC). Therefore, typical parameter values of PVC materials were used in the model. All model components (granular layers and the pipe) were treated as solid bodies with linear elasticity, as can be defined by modulus of elasticity and Poisson's ratio. This choice was made based on the common practice in pavement engineering to model the pavement structure as layers of elastic bodies, which results in good agreement between predicted and measured pavement structural responses to vehicle loads [27–29]. The boundary condition of the soil box was defined by fixed support (all six degrees of freedom restricted since the faces of the box were braced using I-beams) at all surfaces except the top. In the laboratory experiment, both ends of the pipe were extended beyond the soil box boundary. It was considered that the actual representation of this condition in the FE model can be simulated by restricting the pipe ends (truncated at the boundary of the box) against all six degrees of freedom to represent continuity of the pipe. Another important consideration is the definition of the behavior of the interface between different soil layers and the pipe. Prevalent practice in the literature was to define bonded connection for the interface between soil layers and the pipe. In this study, the interface was treated as partially bonded with a friction coefficient. In the later model calibration, it was found that a friction coefficient of 0.1 was sufficient for good agreements between predicted and observed pipe responses. The shape and structure of FE mesh were defined as the program default. Minimum mesh size was 152 mm for the pipe and 304 mm for the granular layers. The static load applied at the center of the top surface was modeled as a vertical point load distributed over a rectangular tire foot print [29]. Table 2 lists the material properties and dimensions of different components assumed in the FE model to simulate the soil box experiment.

Table 2. Properties of various model components of validation model 1.

Model Components	Density, kg/m^3	Elastic Modulus, MPa	Poisson's Ratio	Dimension, m
Sand Layer	1746	70	0.40	3x2.4x0.8 (bottom layer) 3x2.4x0.9 (top layer)
Gravel Bedding	1362	120	0.35	3x2.4x0.2
PVC Pipe	1330	3200	0.48	0.47 (outside dia.) 0.46 (inside dia.)

The rate at which the load was applied in the soil box experiment is not mentioned in [22]. In the FE model, we applied the 107 kN load in 60 seconds at a uniform rate in 20 steps. The model predicted the maximum vertical deflection of the pipe crown at each step for the corresponding loading magnitude level. A plot between load magnitude and vertical deflection of the pipe crown from the static test on the unjointed PVC pipe showed an approximately linear relationship [22]. As enough data was not available to recreate the plot, we constructed a linear relationship using the displacements reported at 0 and 107 kN, as shown in Figure 2. The maximum pipe crown displacements predicted by the FE model at different loading levels are also plotted in the same graph. As can be seen, the pipe response predicted by the FE model closely matches the pipe response recorded in the laboratory experiment. The pipe deflection under the 107 kN load was recorded at 2.87 mm in the soil box experiment and predicted at 2.79 mm in the FE model.

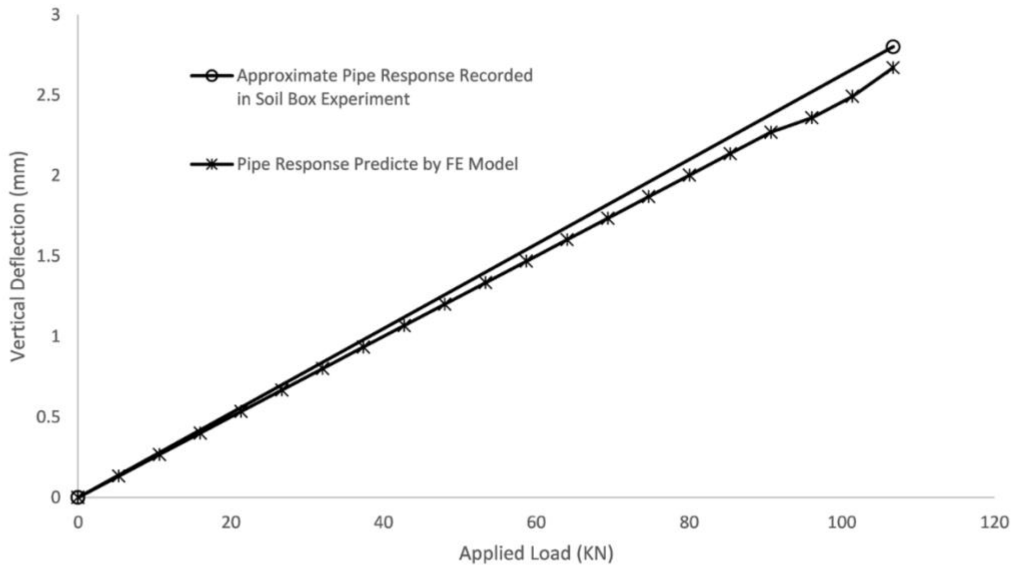
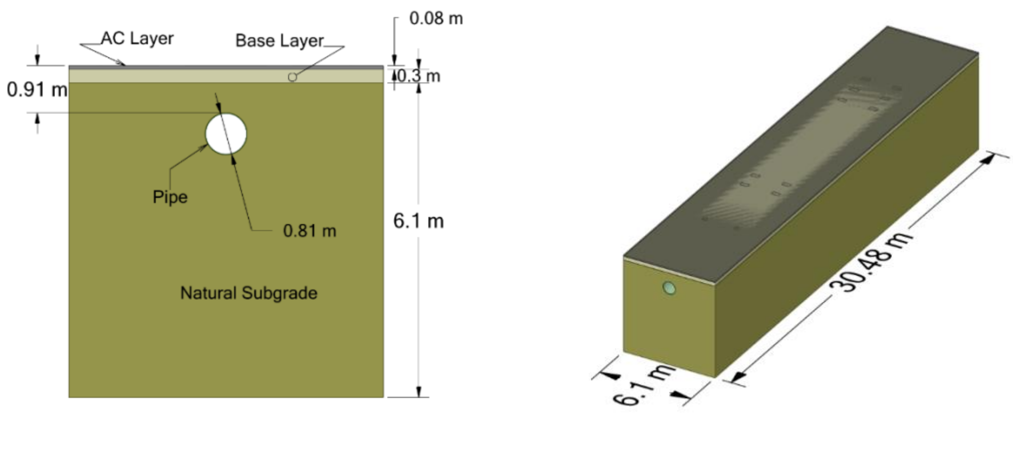


Figure 2. Pipe responses recorded in the soil box experiment [22] and predicted by the FE mode.

4. Experimental FE Model of Buried Pipe Under Heavy Vehicle Load

The validation model helped to determine the appropriate parameter values and to define proper component behaviors of the experimental model for a buried structure subjected to external loads. Our experimental model is a cuboidal section of a layered pavement structure with a pipe buried below the surface, with dimensions of 30.5 m in length, 6.5 m in depth, and 6.1 m in width. It is deemed that such dimensions are sufficient to accommodate pipe responses due to vehicle point loads while fitting within the software computational capacity. The pipe length equals the length or the width of the model depending on the orientation of the pipe relative to the vehicle chassis. The typical layered structure of the buried pipe system consists of an asphalt concrete (AC) layer at the top, a base layer, and a subgrade soil layer. In the model, the pipe is placed at a depth equal to the appropriate depth of cover. A schematic of the experimental model with typical dimensions is shown in Figure 3.



(a) (b)

Figure 3. Schematics of the primary experimental model used in the analysis (a) Side view (b) Isometric view.

For the analysis of the primary experimental model, typical properties of the pavement and pipe materials, as shown in Table 3, are used. The selected parameter values of pavement and pipe materials are close to the minimum values in the range of typical material property values of the corresponding parameter. Parameter values were selected in this manner to ensure that the experimental model represents the most vulnerable and critical condition where relatively weak materials were used. This was coupled with the maximum loading scenario. Like the validation model, all the FE models in this study treat various pavement layers as solid bodies of linear elasticity.

Table 3. Typical values of material properties considered in the experimental model.

Properties	Asphalt Concrete	Base Layer	Subgrade Soil Layer	Pipe Materials			
				PVC	Concrete	HDPE	Iron
Density (kg/m^3)	2323	2162	1762	1411	2300	940	7700
Modulus of Elasticity (MPa)	3500	139	70	2800	27000	1200	1.65×10^5
Poisson's Ratio	0.38	0.40	0.40	0.38	0.20	0.45	0.30

4.1. Loading Scenario for Experimental Model

Among all the conventional vehicles operating on the road network, trucks have considerably higher impacts on the structure beneath than lighter vehicles. For this reason, almost all studies investigating the impact of external vehicle loads on buried pipes considered heavy truck loads. The effect of vehicle loads is considered in the design of pavement and bridge in different ways. Similar to the standard live load considered in bridge design, the AASHTO H-20 or HS-20 truck load is usually considered in the pipe design [30,31]. Consequently, a number of studies also considered similar loading in understanding the effect of external loads on buried pipes. However, trucks heavier than HS-20 are allowed on the road network in the U.S. according to the FHWA regulations. The maximum federal allowable gross weight of heavy truck is 356 kN (80 kips). Eventually the buried structures are subjected to these external heavy loads even though their percentage in the traffic stream is low. Since the objective of this study is to understand the impact of heavy vehicle movement on buried pipes, especially when critical conditions arise, the maximum allowable limit of gross truck weight was selected as total truck load without being unrealistic in the assumption of critically heavy loads. Figure 4 shows the heavy truck considered in this study, which is representative of the loading condition of 6 axle tractor semi trailers in the actual truck fleet.

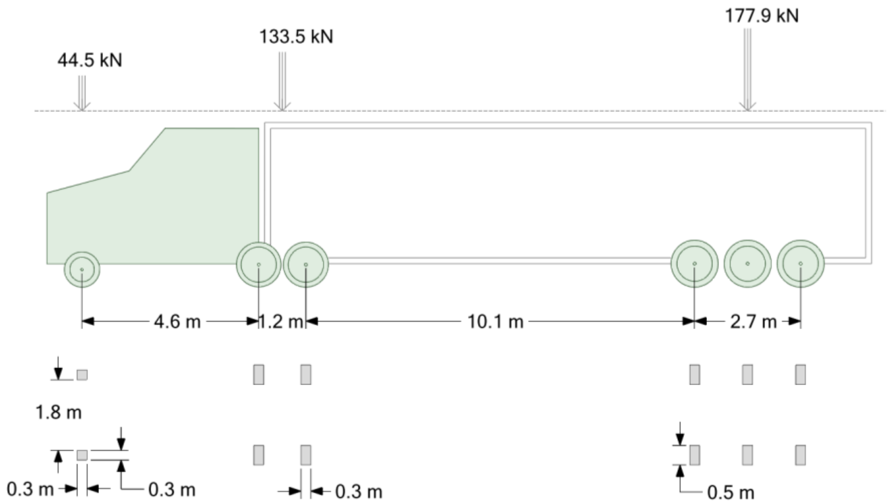


Figure 4. A representative 6-axle tractor semi-trailer and its footprint considered in the experimental model.

4.2. Experimental Analysis Using the FE Model

4.2.1. Phase I Analysis of Pipe Response under Normal Operating Condition

Scenario 1: Pipe behavior against variation of vehicle loads

The first scenario of FE analysis investigates how the pipe response varies with the application of various loads from heaviest trucks in the truck fleet. In selecting the loads, we considered the current federal regulation for allowable maximum weight of heavy vehicles in the U.S.. Our study truck consists of 6 axles in three axle groups. The axle in the front consists of two wheels and is referred to as a steering axle. Towards the middle of the truck, two axles are grouped into a tandem axle containing eight wheels. Towards the end of the truck, three axles are grouped into a tridem axle containing 12 wheels. The federal maximum load limits for gross vehicle weight (356 kN) distributed in three axle groups, which are 53, 133 and 178 kN (10, 30, and 40 kips), respectively are followed in this study. In the first stage, the application of the truck load configuration shown in Figure 4 on the buried pipe was modeled with the center line of the truck chassis aligned with the longitudinal axis of the pipe, which was discovered to be the most critical loading position. Another point of interest here is the clarification of combined effects on pipes from more than one axle. Previous studies on pipe behavior under vehicle loads did not provide any clarification on whether the effect of a single axle placed at the critical position above the pipe is significantly different from the combined effects of more than one axle. We first applied the loads from different types of axles individually, then gradually increased the number of axles from our study truck and analyzed the pipe behavior. Finally, the combined effect of two trucks with a reasonable spacing of 6.1 m (20 ft) on the buried pipe was evaluated. In the second stage, the pipe response to truck loads placed perpendicular to the pipe (i.e., the truck is crossing a pipe) was analyzed with the middle axle of the heaviest axle group placed above the pipe as it was found to be the most critical loading position. Changes in the pipe response, in terms of maximum vertical deflection, with various axle combinations and orientations are shown in Figure 5 for a ductile iron pipe.

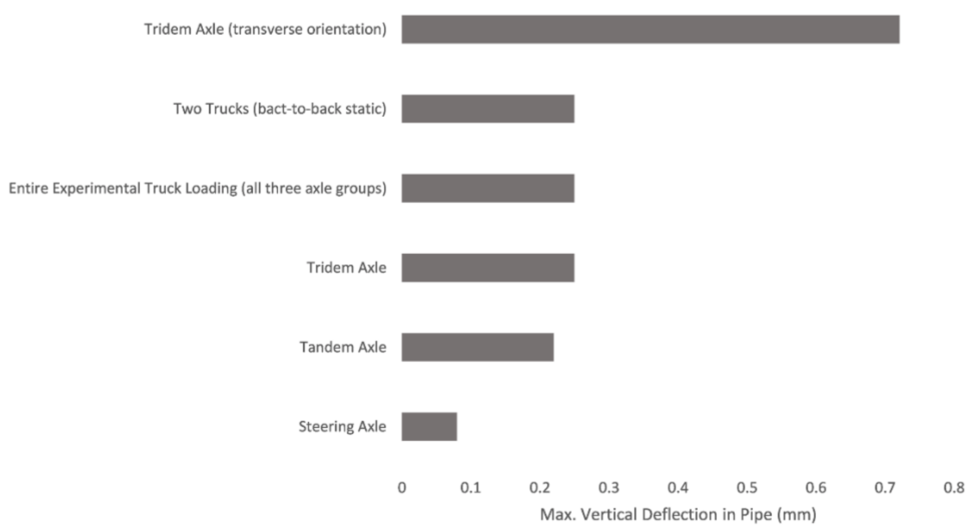


Figure 5. Maximum deflection of ductile iron pipe under different loading scenario.

The following observations can be made from Figure 5. Firstly, the response in the buried pipe is caused mainly by a single, tandem, or tridem axle. For example, when all the axles of a single truck are in action, the maximum deflection is still governed by the heaviest axle (tridem axle in this case) and the magnitude remains almost the same when only a tridem axle load is applied. This means that the axle groups are placed in such a way that their impacts on the pipe are independent from each other. This also applies to axles from multiple trucks. Therefore, to observe the behavior of a pipe in critical conditions, we do not need to consider all the axle loads of the truck in our model. A relatively smaller geometric model may be adopted with the heaviest axle load to assess pipe responses for a shorter computation time in the FE analysis. Secondly, the impact on the pipe is significantly higher when the pipe is placed across the roadway (labelled as 'transverse orientation' in Figure 5).

Based on the above observations, all subsequent experimental analyses were conducted on a small-scale model with finer meshes. The smaller model has the same layered structure as shown in Figure 3 but reduced horizontal dimensions, 6.1 m (20 ft) in width and 6.1 m (20 ft) in length. Only the tridem axle load layout was applied since it caused the highest vertical deflection among all the loading conditions considered in Scenario 1. Also in all the subsequent scenarios, the axle load was positioned perpendicular to the pipe, with the middle axle of the tridem axle group aligned with the longitudinal axis of the pipe.

Scenario 2: Pipe behavior against variation of pipe dimensions

In this section, the pipe behavior under a fixed vehicle load against varying pipe dimensions is analyzed. The state-of-practice standard pipe dimensions for different pipe materials are considered in the analysis. For example, American Water Works Association (AWWA) specifies a range of standard pipe dimensions (diameter and thickness) specific to the constituting pipe materials. The thickness of equal diameter pipes may vary according to its capacity to withstand certain level of working water pressure. Based on this property, pipes of identical diameters are categorized into different pressure classes. For example, ductile iron pipes of 1016 mm (40 inches) diameter come with varying thickness according to its pressure classes. When we selected a standard pipe diameter for analysis, the thinnest pipe (lowest pressure class) of that diameter was selected among available pressure classes. We considered pipes made of the following materials: Ductile Iron (DI), Poly Vinyl Chloride (PVC), and High Density Poly Ethylene (HDPE), whose typical properties (isotropic elasticity) are provided in Table 3. Table 4 lists the standard pipe diameter and corresponding minimum wall thickness recommended for the lowest available pressure class. The impact of cover depth on pipe behavior was also analyzed. In this step, we considered two different cover depths for each selected pipe.

Table 4. AWWA Standard dimensions of DI, PVC and HDPE pipes.

	Standard Dimension of Ductile Iron Pipe																	**Standard Dimension of PVC Pipe**								
Outside Diameter (mm)	122	175	230	282	335	389	442	495	549	655	813	973	1130	1290	1462	1565	1668	389	442	495	549	655	813	973	1130	1290
Min Wall Thickness (mm)	6	6	6	7	7	7	8	8	8	8	9	10	10	12	13	14	14	10	11	10	11	13	20	16	22	25
	Standard Dimension of HDPE Pipe																									
Outside Diameter (mm)	80	114	141	168	181	219	273	324	340	356	406	457	508	559	610	660	711	762	802	914	1003	1067	1203	1372	1405	1606
Min Wall Thickness (mm)	4	4	4	5	6	7	8	10	10	11	12	14	16	17	19	20	22	23	25	28	31	33	37	42	43	49

Pipe responses were determined using the smaller structural model as determined in Scenario 1. Figure 6 presents the analysis results in terms of maximum pipe deflection under fixed vehicle loading but various pipe outer diameters and cover depths. The results include a range of pipe diameters from the smallest to the largest based on the standard dimensions specified by the AWWA for the three pipe materials (DI, PVC, and HDPE). Some notable features of the pipe response against varying pipe dimensions can be observed from Figure 6. For HDPE and PVC pipes, their maximum deflection increases with the increase of their outer diameter. For DI pipes, the trend is opposite. Regarding the impact of cover depth, the general trend is that for almost all pipe materials across the entire dimension spectrum, pipes buried at 0.91 m (3 ft) depth experience smaller vertical deflection than pipes buried at 0.61 m (2 ft) depth. However, there are a few observations that contradict this general observation. The largest vertical deflection was recorded in the HDPE pipe with an outer diameter of 1405 mm, a specified wall thickness of nearly 44 mm, and buried at 0.61 m (2 ft) depth. Notice that if we compare the allowable maximum deflection (70 mm) for a pipe of this dimension with the observed deflection (0.8 mm), the observed deflection can be considered very negligible. However, if we consider comparing the performance of the pipe with the maximum allowable deflection in terms of percentage of pipe diameter, the larger pipes perform better. For example, maximum deflection (in percentage of diameter) occurred in the HDPE pipe of 80 mm outer diameter whereas in larger pipes, this value is close to 0%.

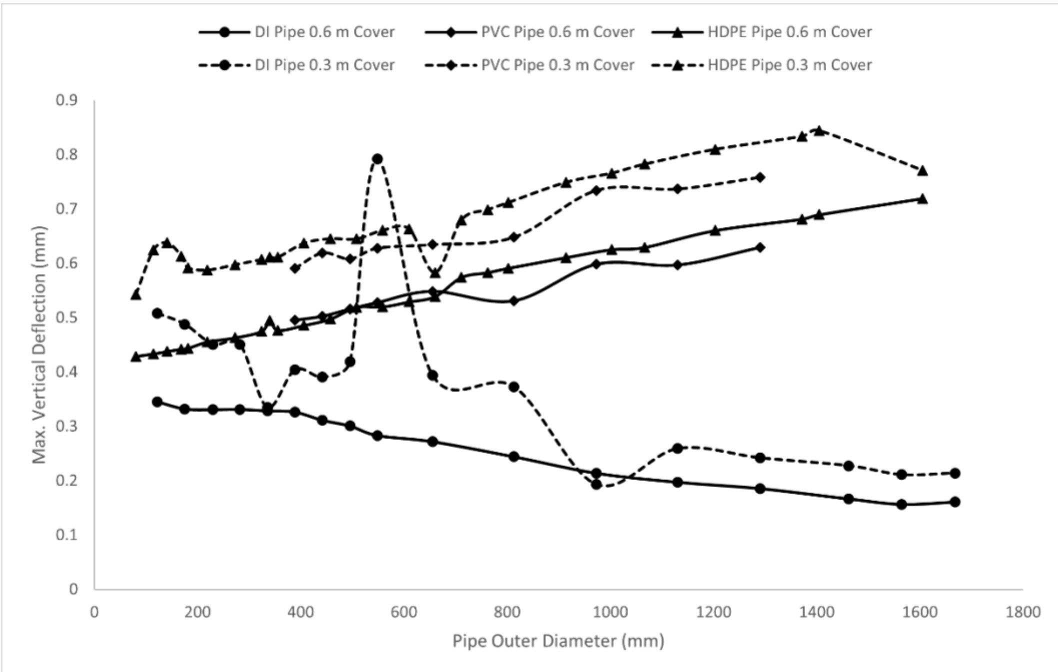


Figure 6. Variation of pipe response along standard pipe dimensions for three widely used pipe materials at two cover depths under fixed loads.

4.2.2 Phase 2 Analysis of Pipe Response under Potential Critical Scenarios

The central objective of this study is to understand if buried water pipes are physically affected by heavy vehicle loads. This will help to understand the broad interdependency between the water and the road infrastructures in ensuring their resiliency and sustainability in future environment. Our analysis so far indicates that even the heaviest load from the currently operational trucks has very negligible effect on the serviceability and the structural integrity of the buried pipes based on the pipe responses recorded in the previous analyses. In this section, we analyze the truck impact when the pipes are in vulnerable conditions. Two common vulnerable scenarios, corroded pipes and sinkhole or void formation underneath the pipes, are considered in the analysis. The highest magnitude truck loading considered in the previous analyses will be applied in these scenarios as well. In all subsequent experimental models, a cover depth of 0.61 m (2 ft) is used due to the consistency in model outputs observed in the previous experimental model as well as being more representative of actual cover depth in the current state of practice.

i) Corrosion in DI pipes

According to [32], the predominant cause of failure in buried utility pipes is corrosion. Moreover, a large portion of buried pipes are made of materials that are susceptible to corrosion such as cast iron and ductile iron [33]. The effect of corrosion in elastic metal pipes includes reduction in yield and toughness strengths, reduction in pipe thickness due to erosion of rusted bits of metals from pipe and formation of small holes in pipes in a similar fashion [32]. An important step towards simulating corroded pipes is to figure out a way to represent these corrosion defects in pipes in the model. Researchers previously used holes (corrosion pit) of different shapes (e.g., rectangular, elliptical) in the middle of inner or outer pipe walls to represent corrosion affected regions in metal pipes [34–36]. Lee and Kim concluded that the geometry of these corrosion pits significantly affects the structural behavior of the corroded pipe [35]. For the sake of simplicity in the analysis as well as limited scope, we used rectangular (curvilinear sides on the curved pipe surface) corrosion pit. The dimension of the corrosion pit was (r x r/2), whereas r is the inner radius of the pipe. This dimension was chosen to represent the reduction in pipe materials due to corrosion and subsequent erosion of loose materials in a manner that is proportional to the size of the pipe.

Since larger pipes have a larger surface area exposed to the surrounding environment, it was assumed that the material reduction in the pipe cross section is higher in larger pipes leading to greater pits. However, the depth of the corrosion pit varied according to the corrosion severity in the pipe. We modeled three levels of corrosion in ductile iron pipes: minimum, intermediate, and severe, which correspond to 25%, 50%, and 75% reductions in pipe thickness, respectively. Based on the results observed in initial trial model run, the most critical placement of the corrosion pit was found to be on the pipe surface directly below the mid axis of the two sides of the axle. We simulated this scenario by creating a single pit at that point. Also, since metal pipes are primarily more susceptible to corrosion, we simulated this phase only for the ductile iron pipes.

ii) Formation of sinkhole around water pipes

In general, sinkhole formation refers to the creation of a hole in the ground due to the subsidence of soil surface. The formation of sinkhole can be attributed to both natural and manmade causes [37]. The manmade reasons may include groundwater extraction, subsurface construction, and leakage in the underground pipelines. A sinkhole formation due to the leakage in underground pipeline initiates through formation of a cavity under the pipe. This cavity grows larger due to continuous water flow from the leak and subsequent erosion of soil particle. Oftentimes these large holes cannot be detected from the ground surface until the top soil layer completely collapses [38]. [39] provided a list of sinkholes formed due to defects in underground pipe. When such a sinkhole forms below a pipe at the initial stage, it leaves a portion of pipe without any support from below. We considered this scenario a critical condition for buried water pipes and analyzed the pipe response when this scenario is further intensified due to the additional loads from heavy vehicles. Finite element analysis of pipes with sinkhole has not been discussed in the existing literature.

In our FE model, the sinkhole was treated as a void volume in the subgrade layer of previous buried pipe model. The sides of the sinkhole were assumed to have a smooth, curved surface instead of sharp edges. A number of sinkholes dimensions were analyzed and it was found that pipe responses generally increased with the increase of sinkhole dimensions. Results from a large sinkhole, whose length, width, and depth are respectively 60% of the model length, equal to the pipe radius, and equal to the pipe diameter, are presented here.

The FE analysis results for the two potential critical scenarios are presented in Figure 7 and Figure 8, respectively, along with results from scenarios without corrosion or sinkhole.

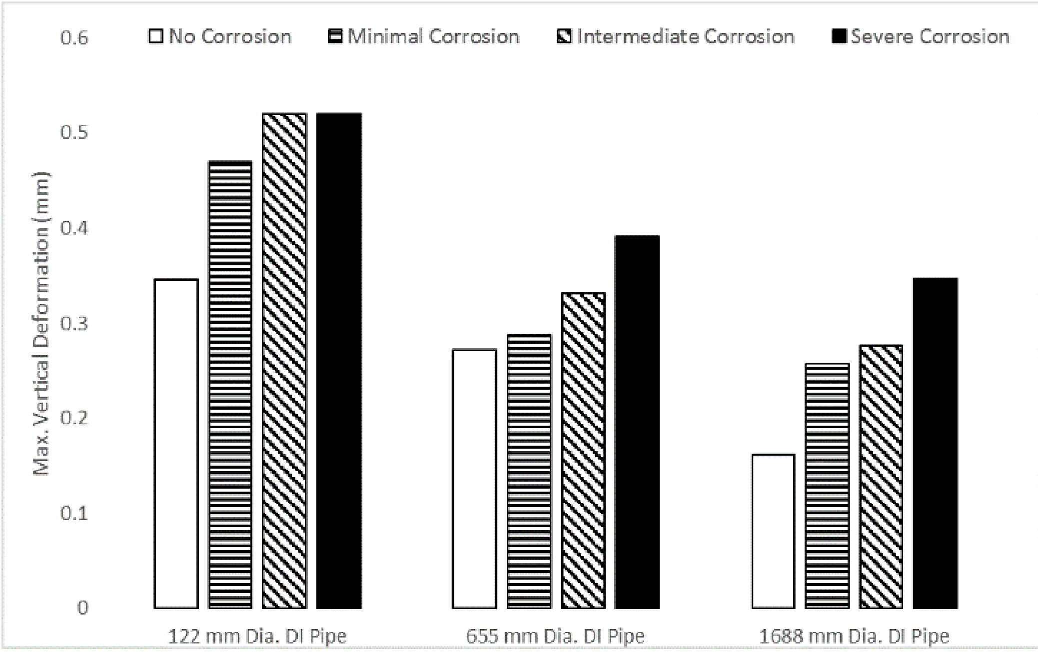
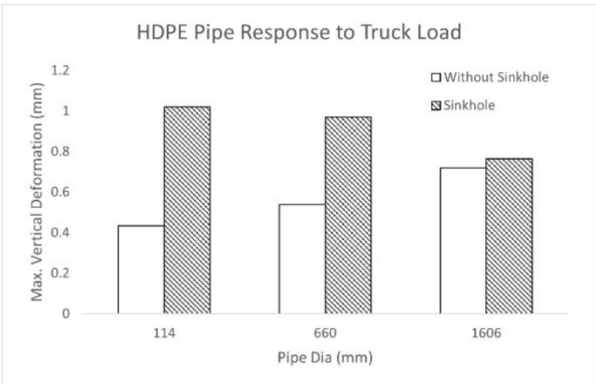
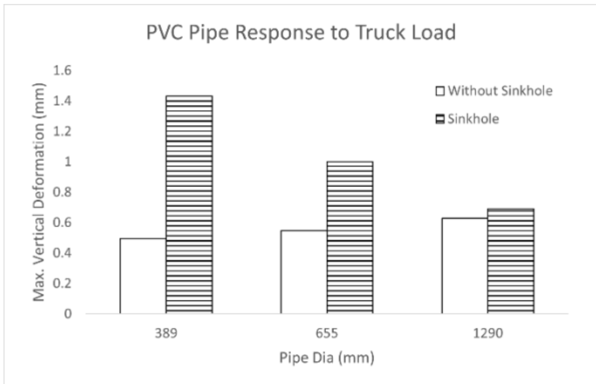
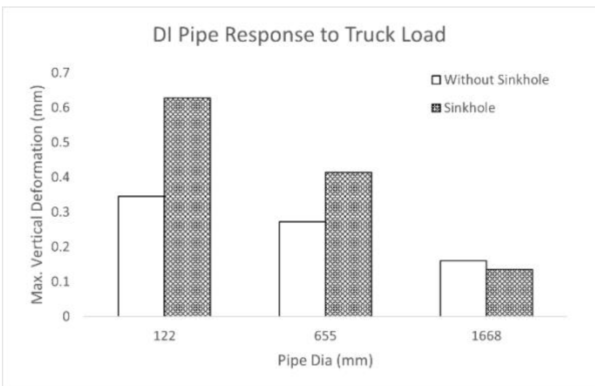


Figure 7. Comparison of DI pipe responses to maximum truck loading under various levels of pipe corrosion.





(**a**) (**b**)



(**c**)

Figure 8. Pipe response to maximum truck loading with and without sinkhole void below (a)HDPE pipes (b)PVC pipes and (c) DI pipes

From both figures it can be seen that there is no abrupt change in the pipe response when the assumed critical scenarios occur. Among all the pipe diameters and materials included in the analysis, the maximum vertical deflection (1.4 mm) is recorded in the small PVC pipe (389 mm dia.) when there is void formed below the pipe. This deflection is 0.3% of the pipe diameter. If we consider the percent deflection with respect to pipe diameter only, the maximum response (0.8 %) occurred in the 114 mm diameter ductile iron pipe. In both cases, the pipe response is very negligible compared to the allowable limit (5% of the pipe dia.) set by AWWA standard. Nevertheless, a number of features are worth noting from these results. Firstly, for all three pipe materials considered in this study, small pipes exhibited more vertical deflection increase due to corrosion or sinkhole than large pipes. Secondly, for all pipe materials and scenarios except for the HDPE pipe with sinkhole, the maximum vertical deflection in pipes decreased as the pipe dimension increased. This indicates that larger pipes are more stable against external loading both in normal and critical conditions. This is true, if we consider both the magnitude of vertical deflection and deflection as a percentage of pipe diameter. However, the flexible PVC and HDPE pipes demonstrate slightly different results: the vertical deflection magnitude increased with the increase of pipe dimension in the normal operational scenario. When we assume void formation below the pipe, the larger pipes experienced less deflection compared to the smaller pipes. If we consider the deflection with respect to the pipe diameter, the large pipes will have a lower deflection percentage compared to the small pipes.

5. Discussion and Conclusions

The main objective of this study was to uncover if heavy vehicles would affect the underlying water pipes of the state-of-practice designs so as to provide better understanding of the interdependency between the water and road infrastructure systems. In our analysis, hydraulic loading on the pipe was not considered since the focus was to understand the effect of heavy vehicle loads. The pipe response presented in this paper is mainly the maximum pipe deflection. The stress response in the pipe was also analyzed but not reported, mainly because the maximum tensile stress revealed in the analysis was very low, which would not lead to fatigue damage in the pipe even after a very large number of load repetitions.

This study found that the critical response in a pipe to vehicle loads was dominated by one axle group from a vehicle, so there is no need to consider the entire truck or fleet of trucks in modeling. It was also found that a pipe experiences the largest effect when the pipe is laid out across the direction of vehicle movement. In case of flexible pipe materials (i.e., PVC and HDPE), the magnitude of pipe deflection increases with the increase of pipe diameter, whereas for ductile iron pipes the result is opposite. However, if we consider percent deflection with respect to the pipe diameter, larger pipes made up of all three materials are more stable compared to smaller pipes.

The overall finding is that the critical pipe response in terms of vertical deflection is significantly lower than allowable value, even under extremely vulnerable conditions such as serious pipe corrosion or existence of sinkhole. While existing studies on the effect of external loads on buried infrastructures covered some scenarios, this study fills in the gap by providing direct conclusion that even the heaviest truck within current federal regulations does not significantly affect the buried pipes. Hence, water pipes affected by heavy vehicles may not be considered as a structural interdependency case between these two infrastructures. While other examples of the potential interdependency cases need to be considered (e.g., operational and social interdependencies), the structural interdependency does not propagate from road to water pipes under vehicle loads.

With the above conclusions drawn, it should be noted that there are a few limitations in this study. Although we have considered a number of pipe materials, dimensions, loading scenarios and multiple critical situations, the list is not exhaustive. Variation in the layer structure above the pipe was not considered to avoid complexity in the analysis. Other pipe materials such as cast iron, steel, concrete was not considered because they are much less commonly used in practice for water pipes. The finite element model constructed in this study, however, may be easily adapted with new components and parameters for analyzing new field scenarios.

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