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## Dynamic Modeling of Long Combination Vehicles

Arash Tarighi<sup>a\*</sup>, Ton-Lo Wang<sup>b</sup>

<sup>a,b</sup>*Department of Civil & Environmental Engineering, Florida International University, 10555 West Flagler Street, Engineering Center, Miami, FL, 33174, United States*

<sup>a</sup>*Email: atari002@fiu.edu*

<sup>b</sup>*Email: wangt@fiu.edu*

### Abstract

The importance of using longer vehicles for the freight shipment in the United States has been the subject of a lot of discussions recently. Not enough research has been conducted on the effects of these heavy vehicles. In this research, three different types of Longer Combination Vehicles (LCVs) have been modeled. The equations of motion of these three vehicles as well as eight other common vehicles have been derived and these vehicles have been subjected to different road surface conditions. The dynamic response of the vehicles due to the unevenness of the road surface has been calculated and compared to the results of the other types of trucks such as the single unit trucks and truck and trailers. In addition, the effects of a single bump on the road, when different vehicles are traveling, have been studied. The results can help understand the effects of these trucks on the road overlays. The models and the results from the models can also prepare the first step to study the effects of larger vehicles on roadway bridges. The results of this study shows that the tire impact factors due to the passage of LCVs on the roadways are almost in the same range as the other types of vehicles so dealing with the LCVs does not require careful considerations when it comes to the pavements.

**Keywords:** Long Combination Vehicles; Dynamic Response; Road Surface Roughness; Bump; MATLAB.

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\* Corresponding author.

E-mail address: atari002@fiu.edu.

## **1. Introduction**

Longer Combination Vehicles (LCVs) are referred to trucks with combination of multiple trailers and they are usually bigger in size and capable of carrying more loads comparing to the common types of trucks which includes the “Single Unit Trucks” such as SU4 Truck and the “Truck and Trailer” or “Truck and Semitrailer” such as Type 3S2 (FDOT Truck). Currently, according to the state laws in the United States, thirteen states allow the operation of Longer Combination Vehicles (LCVs) with some limitations. In addition to that, six states allow these vehicles on Turnpikes only [1].

Using LCVs on the roads can decrease the fuel cost, labor, emission, congestion and also increase the freight shipping efficiency and volume [1]. These benefits altogether make the subject of using these vehicles very appealing to the DOTs. But one should make sure that necessary infrastructures are provided and they are indeed capable of handling the effects of using these vehicles on both roads and bridges.

The interest in utilizing LCVs' benefits has been increased in the recent years with the increase in costs related to the freight shipment, resulting in more willingness among policy makers at DOTs and industry professionals to use other options such as using LCVs. Even though with Intermodal Surface Transportation Efficiency Act which was passed in Congress in 1991 the use of LCVs has been limited due to safety and pavement damages. The only exceptions were the states which had already allowed the use of LCVs [1].

The inconsistency in the literature can be seen when it comes to the effects that LCVs have on the road safety but when it comes to the effects of these vehicles on the road surface, it seems that there is a consensus that with restricting the axle weight limits of LCVs to the axle weight limits of other trucks, the Gross Vehicle Weight (GVW) might not have a huge impact on the road surface damages [1].

It is believed that the number of axles passing over the pavement, the weight of the axles and spacing between the axle groups will determine the damages sustained by the pavement. The relation between the axle weight and the damage to the pavement has been found to be an exponential one with the power of four. Generalization in the case of the effects of distance between the axle groups has been found to be a difficult task. The effects of the increase in speed on the pavement also seem to be unpredictable. In order to achieve the purpose of carrying more loads with heavier trucks, two options of heavier axles as well as more number of axles are possible. Studies have shown that while using heavier axles can increase the cost of damages to the pavements, using more number of axles to satisfy the increase of the load demands can even result in a decrease in cost of pavement damages [2].

Sometimes having one more axle can even relieve the pressure on the pavement. As an example, the two cases of 5-axle and 6-axle tractor semitrailer were compared in USDOT (2000). The steering axle, tandem axle and tridem axle were assumed to weigh 12, 34 and 44 kips respectively. In the case of 5-axle truck, two tandem axles were assumed, adding up the total weight to 80 kips. In the case of 6-axle truck, a tandem and a tridem axle were assumed which made the total weight, 90 kips. It was observed that the 5-axle truck with the smaller gross vehicle weight caused % 18 more damage to the pavement [3], [4].

Approach slab settlements and movements of the bridge deck might cause bump formation at the end of the bridges. This can cause bridge maintenance costs, bridge deck damages, reduced control for the drivers and inconvenience for the passengers [5]. Heavy trucks passage over the bump can cause significant damages to the infrastructures.

In this paper, the dynamic model and equations of motion of LCVs have been generated. The models have been analyzed under different vehicle speeds and road surface conditions. The effects of the presence of a bump on the road have also been studied. The results have been compared to the results of the common truck types to help better understand the effects of LCVs on the roads.

## 2. Models

### 2.1. Vehicle Models

A few different vehicle modeling techniques have been proposed throughout the years. One system which has been used the most is the system proposed and used by Wang and Huang in several studies [6], [7], [8], [9], [10]. This system and similar systems of modeling have also been used by other researchers to study the dynamic response of bridges due to vehicles. This system comprises of rigid massed as the truck, trailer and axle parts. Each truck or trailer mass has three movements of pitching, rolling and vertical displacements. The axles possess only the vertical and rolling displacements. The springs and dampers have been put together in parallel in a so-called “Kelvin model”. This model represents the suspension and the tires. The vehicle properties including the stiffness and damping of the suspension and tire for the H-20 and HS-20 trucks can be seen in Table 1.

Table 1. Trucks Properties for the H-20 and HS-20 Trucks

	H-20		HS-20		
	1 <sup>st</sup> Axle	2 <sup>nd</sup> Axle	1 <sup>st</sup> Axle	2 <sup>nd</sup> Axle	3 <sup>rd</sup> Axle
Suspension Stiffness (Kips/in)	2.97	11.42	2.97	11.42	11.42
Tire Stiffness (Kips/in)	4.99	19.98	4.99	19.98	19.98
Suspension Damping (Kips.Sec/in)	0.06	0.23	0.06	0.23	0.23
Tire Damping (Kips.Sec/in)	0.006	0.02	0.006	0.02	0.02

Three common types of LCVs have been used in this paper. These models are 7-Axle Rocky Mountain Double, 8-Axle B-Train Double and 9-Axle Turnpike Double. In addition to these vehicles, eight more vehicles including three “Single Unit Trucks” (H-20, SU4 and Type 3) and five “Tractor Semitrailers” (Type 3S2, Type 3S1, Type 2S2, Type 3S3 and HS-20) have been modeled and analyzed. This will help compare the three different vehicle categories of “Single Unit Trucks”, “Tractor Semitrailers” and LCVs. Table 2 shows the number of axles and axle weight and Gross Vehicle Weight (GVW) of all these vehicles.

Table 2. Trucks Axle Weights and Gross Vehicle Weight

Axle Number	Vehicle Type										
	H-20	HS-20	Type 3	Type 3S2	Type 3S3	Type 2S2	Type 3S1	SU4	7-Axle Rocky Mountain Double	8 Axle B-Train Double	9 Axle Turnpike Double
1	8	8	16	12	12	12	12	13.9	14	12	15
2	32	32	17	17	17	24	18	18.7	18	15	17
3		32	17	17	17	18	18	18.7	18	15	17
4		17	17	17	18	24	18.7	17	14	16	
5		17	17					17	14	16	
6					17				18	19	16
7									18	17.5	16
8										17.5	17
9											17
Gross Vehicle Weight [Kips]	40	72	50	80	97	72	72	70	120	124	147

The model for 7-Axle Rocky Mountain Double can be seen in Figure 1. This vehicle consists of one tractor, one semitrailer and a trailer, each having three degrees of freedom. Each axle has two degrees of freedom adding up the total number of degrees of freedom to 23 for this particular vehicle. The relative displacement at the spring locations of the tire and the suspension are also calculated using the geometry of the vehicle.

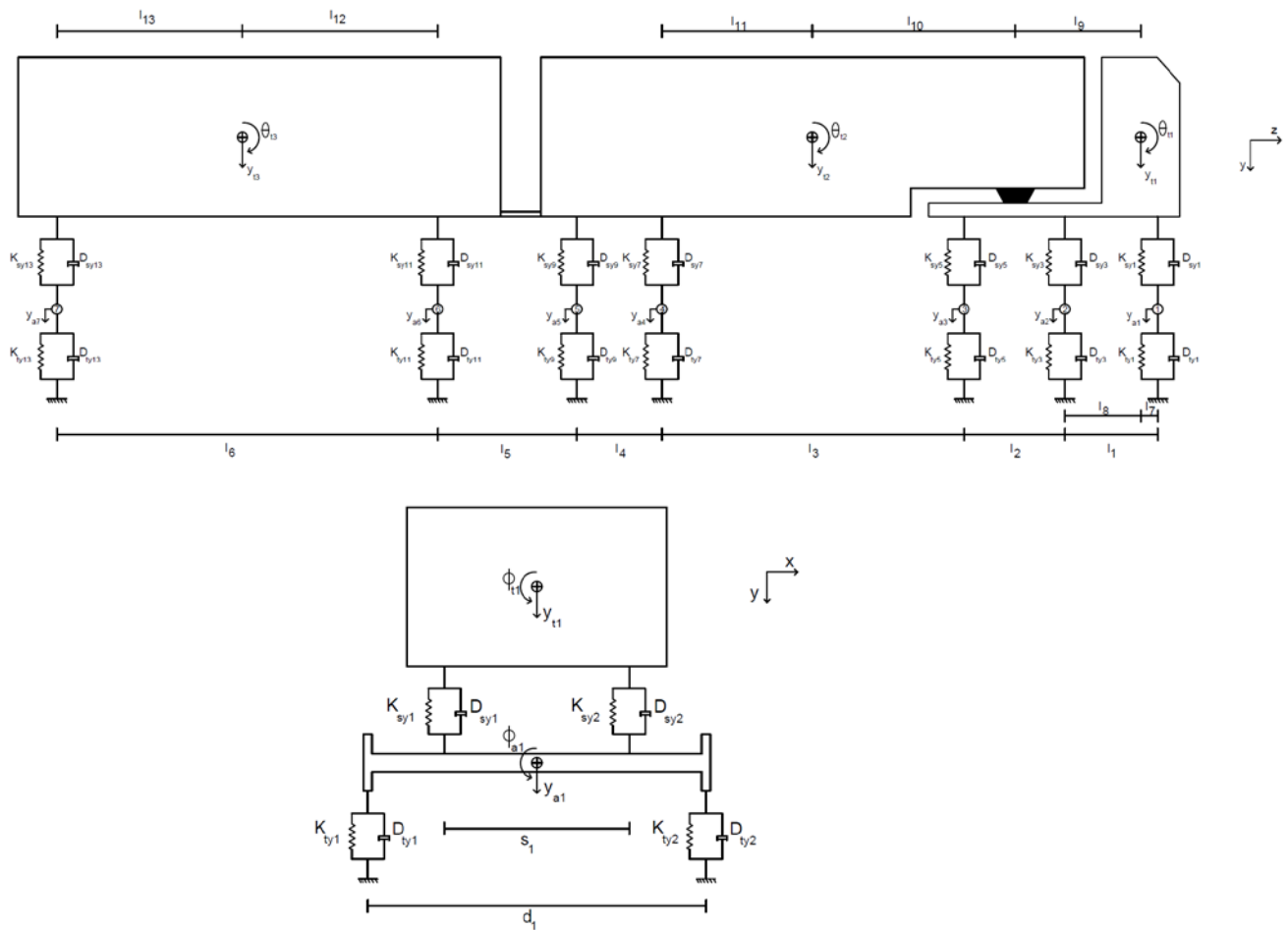


Figure 1. Seven Axle Rocky Mountain Double Dynamic Model (a) Truck Side View (b) Truck Front View

By forming the expressions for the “Kinetic Energy”, “Potential Energy” and “Damping Energy” and using the Lagrange’s formula (Equation 1) for all degrees of freedom, equations of motion will be obtained.

$$\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = 0 \quad (1)$$

Where T, V, D are the Kinetic, Potential and Damping Energy of the system, respectively. q, is a degree of freedom.

The point that connects the tractor and the semitrailer is called the “Pivot Point” or the “Fifth Wheel”. The Fifth wheel works in a way that the displacement of that point, whether it is calculated from the tractor part or the semitrailer part, has to be the same. This constraint adds a condition to the equations of motion and should be taken into account. For the trailer, instead of a pivot point a horizontal link which assures the same travel speed for the trailer was assumed.

In order to solve the equations of motion, MATLAB software [12] has been used. MATLAB ODE function (ode45) which is designed to solve “Ordinary Differential Equations” has been used to solve these equations. This solver uses fourth order Runge-kutta to solve the ordinary differential equations. It was assumed that the vehicle starts at the state of rest and as the vehicle moves forward, the road surface condition displaces the vehicle suspension therefore the initial condition of each state changes.

## ***2.2. Road Surface Roughness***

Road surface irregularities and flaws can play a big role in the extent of damages sustained by the pavement. The more uneven a surface is, the bigger the strain which will be put on the pavement.

In this paper the same road surface roughness which was used by Wang and Huang in several studies [6], [7], [8], [9], [10] have been used. In these studies, the Power Spectral Density (PSD) function, which was proposed by Dodds and Robson [11], was used. Using random numbers generation and filters, data were fitted to the PSD function and road surface profiles were generated for four different road surface conditions of “Very Good”, “Good”, “Average” and “Poor”. Road surfaces are defined over a 800 foot distance and the surface profile was reported in every 5 inches along the road. Two different sets of road profile are selected for the right and left tires. The road surface profile for the right tire is shown in Figure 2.

## **3. Analysis Results**

### ***3.1. Analysis Results for Different Road Surface Conditions***

Impact Factor is a good criterion to understand the dynamic effects of vehicles on the road surface. Impact Factor is defined in equation (2) and it can be calculated for the suspension or the tire. The tire impact factor is of more importance here and it can be used as an indicator of the strain which is being put on the pavement.

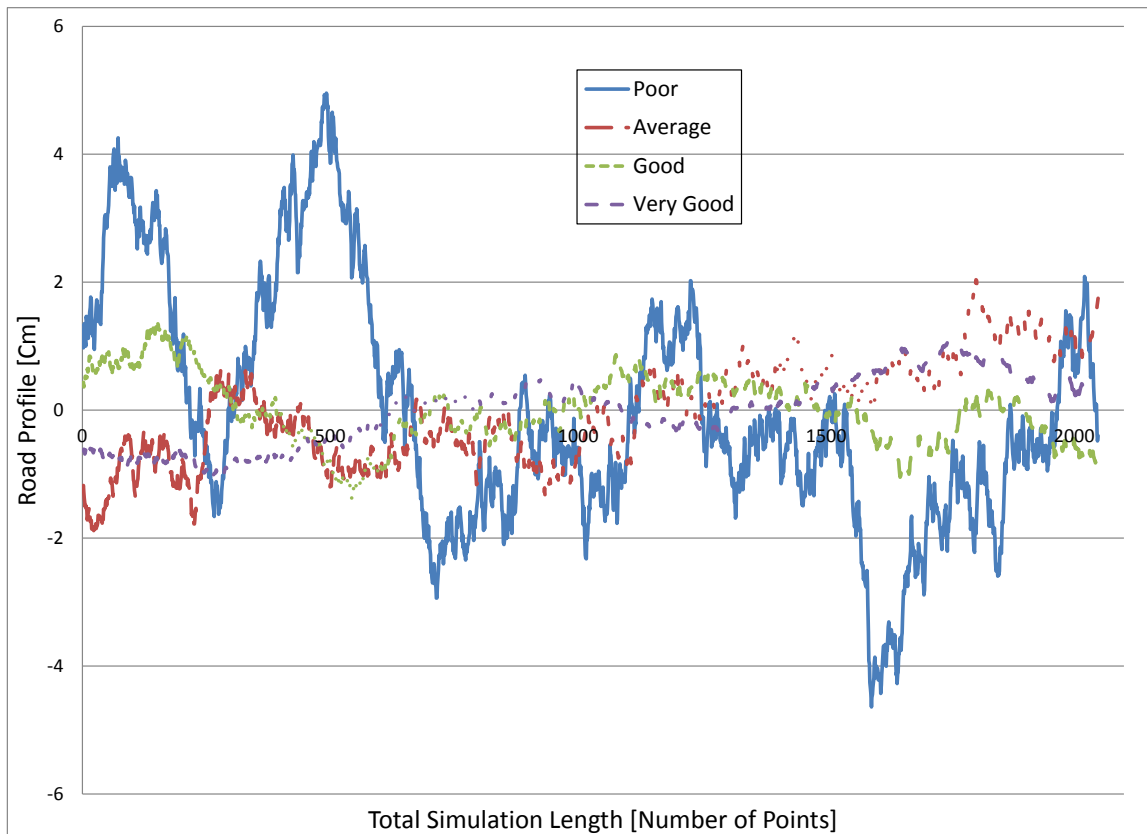


Figure 2. Road Surface Profiles for the Right Tire

$$\text{Impact Factor(\%)} = \frac{\text{Maximum Dynamic Response} - \text{Maximum Static Response}}{\text{Maximum Static Response}} * 100 \quad (2)$$

In order to study the responses of different vehicles, the dynamic equations of motion of the trucks were analyzed while traveling on different surface conditions. Eleven different vehicles traveling at the speed of 15 to 75 mph on four different road surface roughnesses were studied. The Impact Factor can be calculated for each truck tire.

The time history results of H-20 truck traveling at 15 mph on the “Very Good” surface condition are shown in Figure 3. The results have been reported for all four front and rear tires.

The results of the tire impact factors of H-20 truck for the front and rear axles traveling on “Very Good” and “Good” Surface Conditions are shown in Figure 4. It can be seen that the impact factors of the heavier axle (the rear axle in this case) are higher than the lighter axle (the front axle in this case). One can also see the effects of the surface conditions on the results and the fact that when vehicles travel on worse surface condition, the values of the impact factor increase significantly.

The results of the maximum tire impact factors for the last axle of the “Single Unit Trucks” are shown in Table 3.

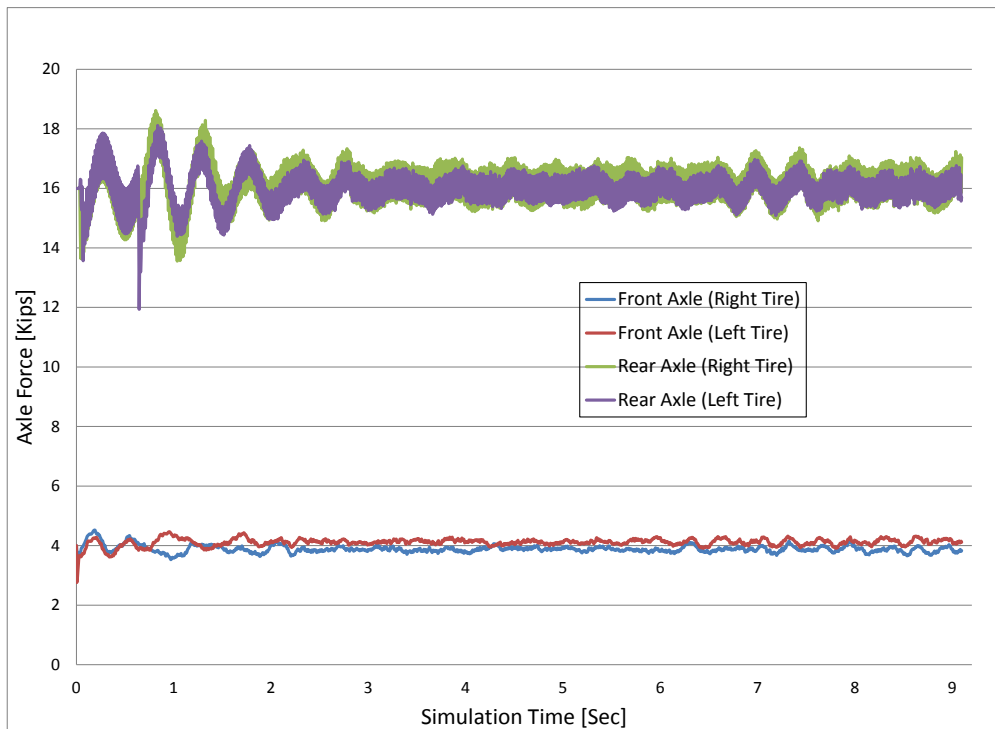


Figure 3. Time History of Different Tire Responses of H-20 Truck Traveling at 15 mph on “Very Good” Surface Condition

Table 3. Maximum Tire Impact Factors of “Single Unit Trucks” for the Selected Axle (All Surface Conditions)

Vehicle Speed [mph]	Tire Impact Factor [%]											
	H-20				SU4				Type 3			
	"Very Good"	"Good"	"Average"	"Poor"	"Very Good"	"Good"	"Average"	"Poor"	"Very Good"	"Good"	"Average"	"Poor"
15	16.4	27.9	32.8	53.9	32.9	44.4	42.6	76.6	41.3	43.8	37.0	98.8
25	11.9	28.1	33.1	52.7	43.1	48.9	55.0	76.7	26.0	54.9	45.0	102.2
35	10.2	20.0	32.2	66.6	42.9	47.3	51.0	55.1	30.8	38.1	69.4	91.0
45	25.7	22.6	37.3	64.2	42.4	49.7	52.1	77.3	26.8	41.4	56.3	113.5
55	15.9	40.7	36.3	54.0	34.6	62.6	54.1	86.3	22.5	58.8	57.3	92.5
65	16.2	25.2	38.8	57.4	40.6	64.6	66.8	85.7	32.7	61.7	56.1	107.8
75	16.4	24.4	40.0	48.3	42.4	49.7	68.0	99.8	34.4	51.5	65.9	106.5

By collecting the analysis results of all the vehicles and averaging these results for the three groups of vehicles (“Single Unit Trucks”, “Tractor Semitrailers” and “LCVs”), Figures 5 to 8 are created based on different road surface roughness situations. The results shown are for the last axle of the “Single Unit Trucks”, last axle of the “Tractor Semitrailers” and last axle of the first trailer (Semitrailer) of the “LCVs”. It can be seen from these figures that the values of impact factor can get very high as the road surface condition goes from “Very Good” to “Poor”. In terms of the effects of the vehicle speed on the values of impact factor, it is not easy to find a generalized rule for these effects and an increase in the vehicle speed can result in higher or lower values of impact factor. But the most important conclusion which should be drawn from these results is about the LCVs. They tend to have slightly higher results for the cases of better surface conditions such as the “Very Good” and “Good” but in the case of the “Poor” surface condition they show smaller values of impact factor. In general the results from the LCVs are not that different from the other two types of the vehicles. It should be noted that this might not be necessarily true for the case of vehicles traveling on the bridges because the nature of the problem

is different in that case and the interaction between the vehicles and the bridge should have an important role in that problem.

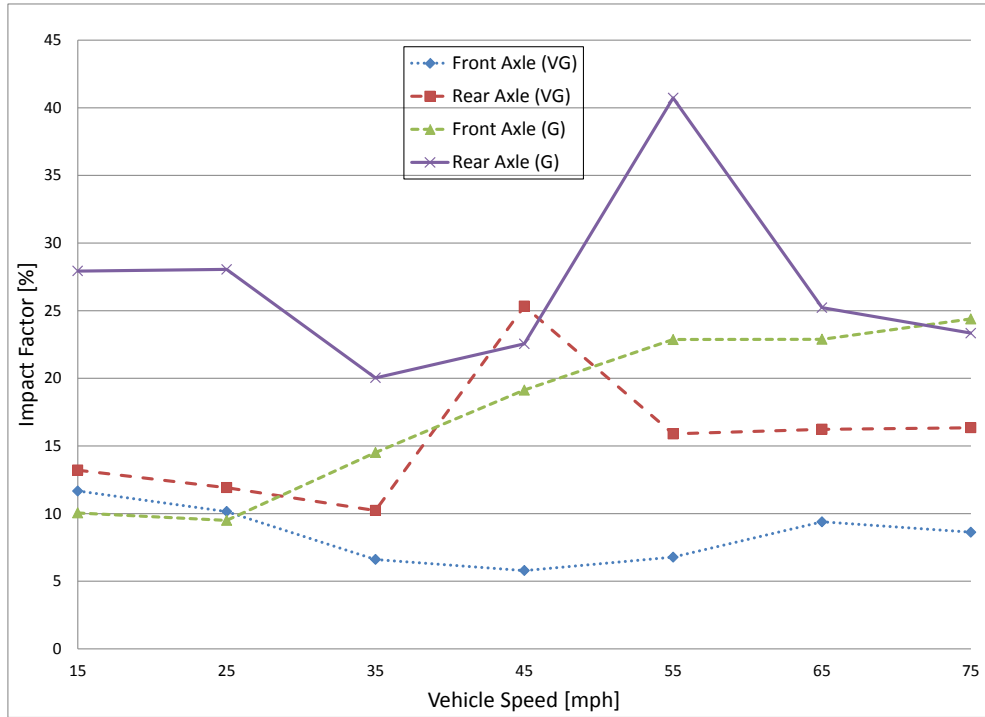


Figure 4. Tire Impact Factors of H-20 Truck for Front and Rear Axles (“Very Good” and “Good” Surface Conditions)

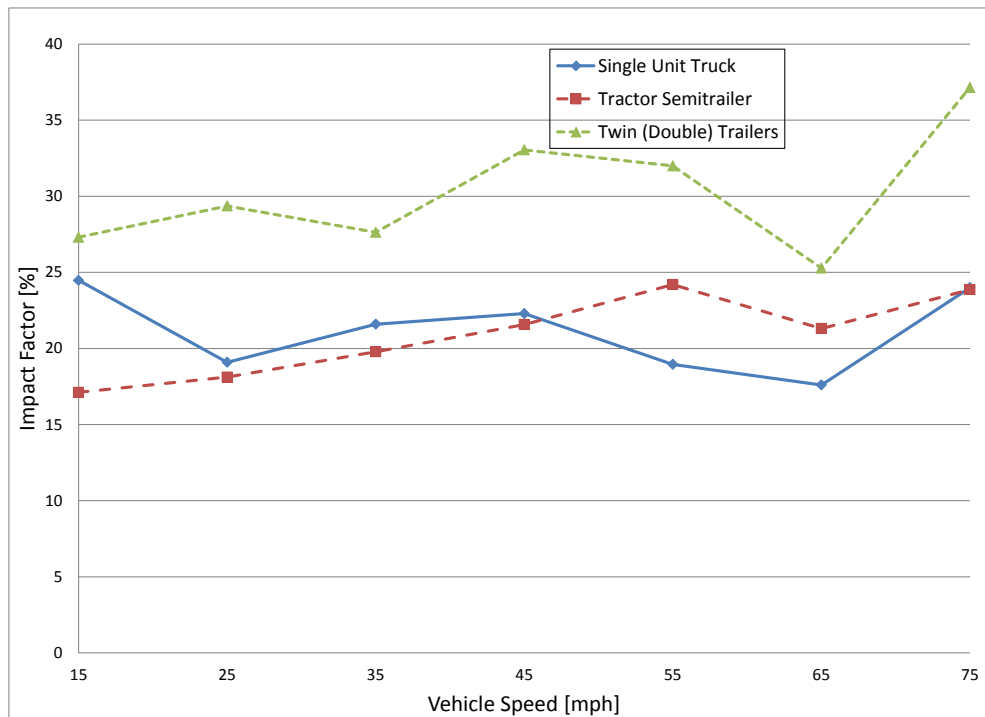


Figure 5. Tire Impact Factor of Different Vehicle Categories for the Selected Axle (“Very Good” Surface Condition)



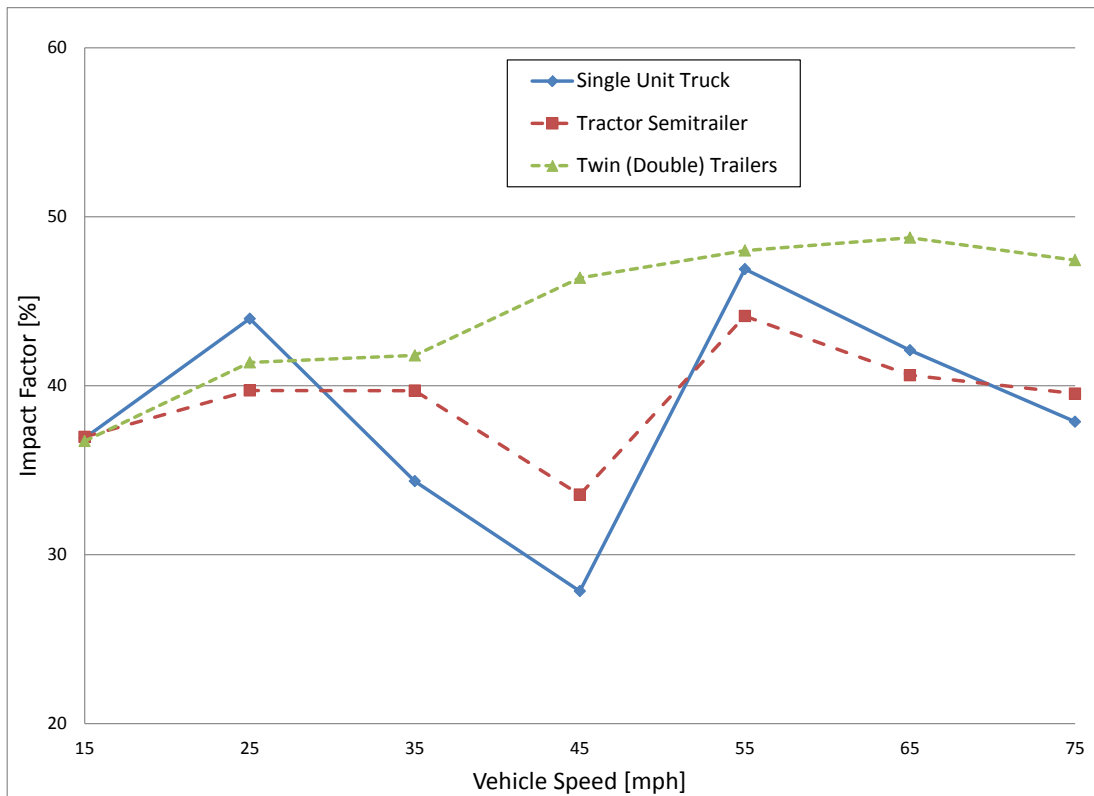


Figure 6. Tire Impact Factor of Different Vehicle Categories for the Selected Axle (“Good” Surface Condition)

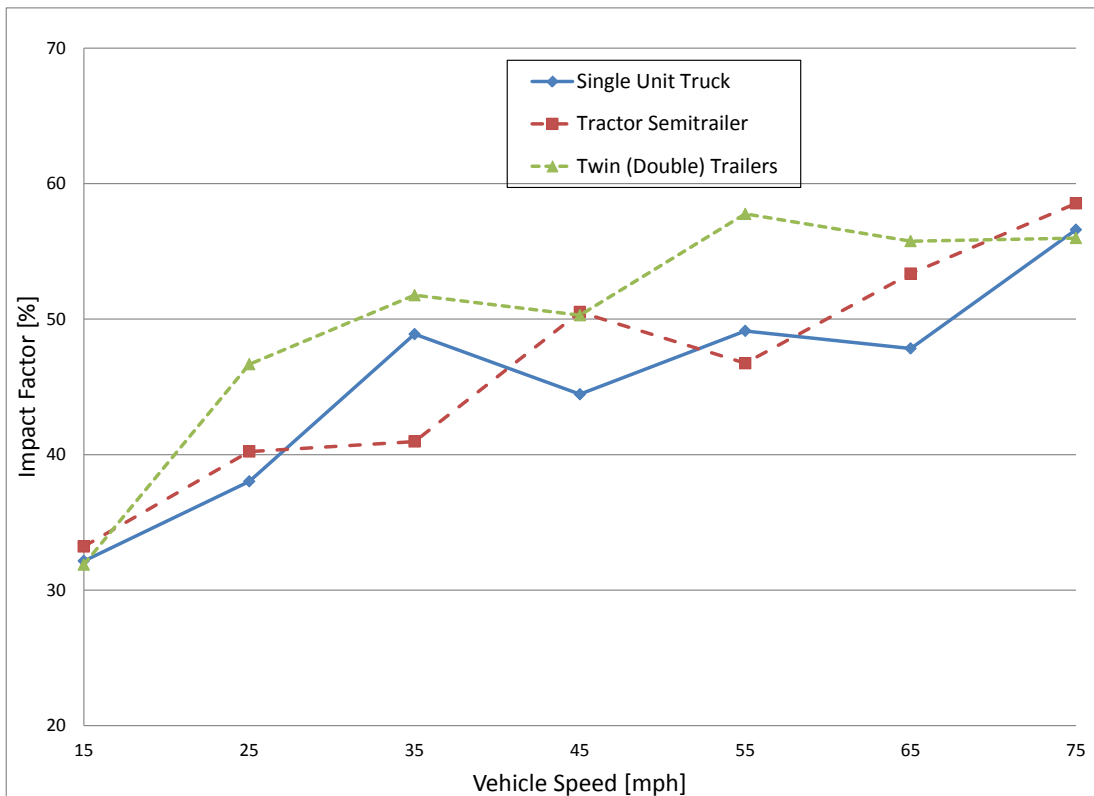


Figure 7. Tire Impact Factor of Different Vehicle Categories for the Selected Axle (“Average” Surface Condition)

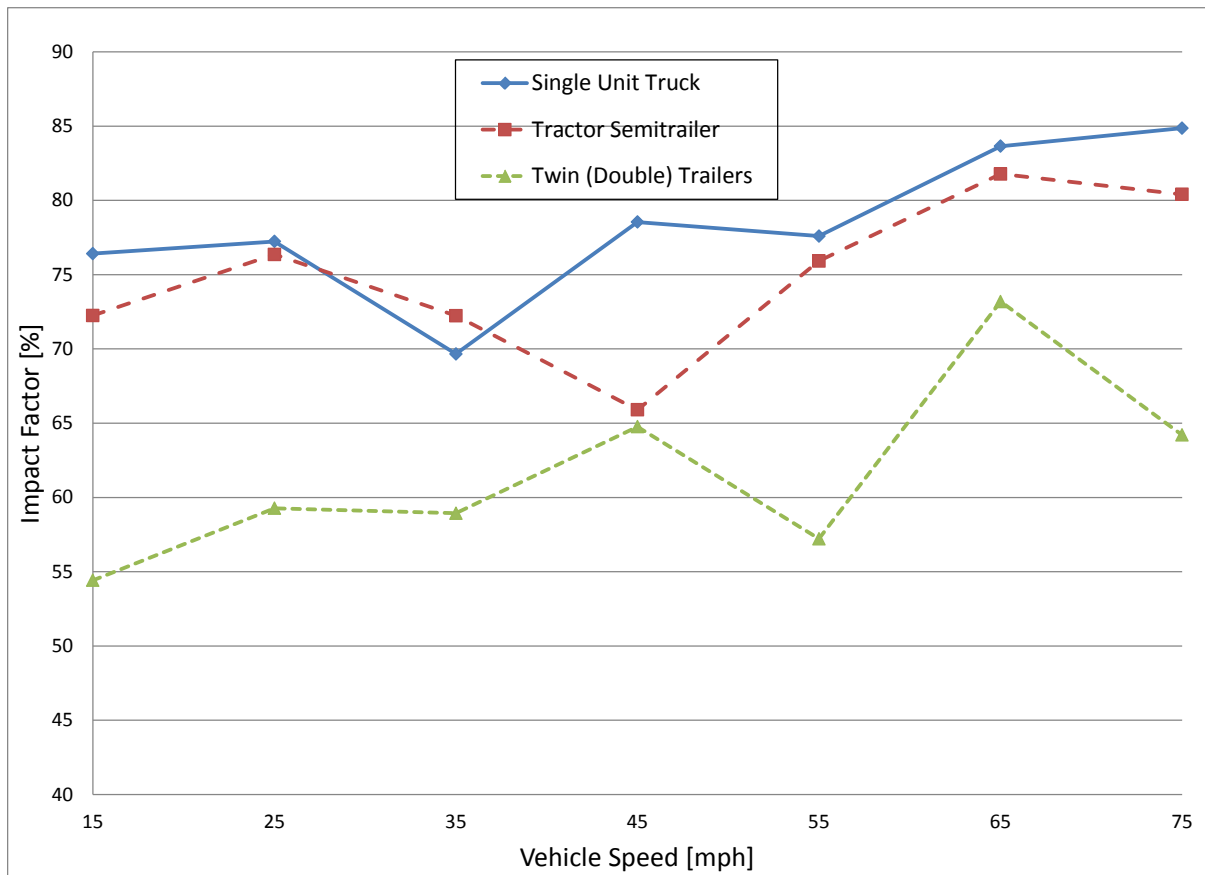


Figure 8. Tire Impact Factor of Different Vehicle Categories for the Selected Axle (“Poor” Surface Condition)

### 3.2. Single Bump Effect

In order to study the effects of a single bump, instead of the road surface generated using the PSD function, a smooth road surface profile with a single bump of different sizes was assumed for the road surface condition. Three different bump sizes of 1/2, 1 and 2 inches were assumed. 3 inches and larger bump sizes resulted in numerical issues and in some cases the analysis could not be completed.

The time history of different tire responses of H-20 truck traveling at 15 mph and 75 mph when a single 1” Bump is present is shown in Figure 9 and Figure 10. Since the length that vehicle travels in is equal in both cases, it can be seen that the truck traveling at 15 mph has enough time to go back to its original state whereas in the case of the truck traveling at 75 mph, it is still vibrating at the end of the simulated length of 200 feet. In both cases the front axle (light axle) goes back to its original state much faster than the rear axle (heavy axle). Also by comparing the peaks of the forces between the front and rear axles, it is evident that there is a time lag between the two peaks which shows the time difference between the two axles passing over the bump. It should also be noted that unlike the previous results for different road surface conditions where the left and right tires had different road surface conditions, here the input of both left and right tires are the same, therefore the two tires show identical behaviors and the vehicle does not show any rolling motions.

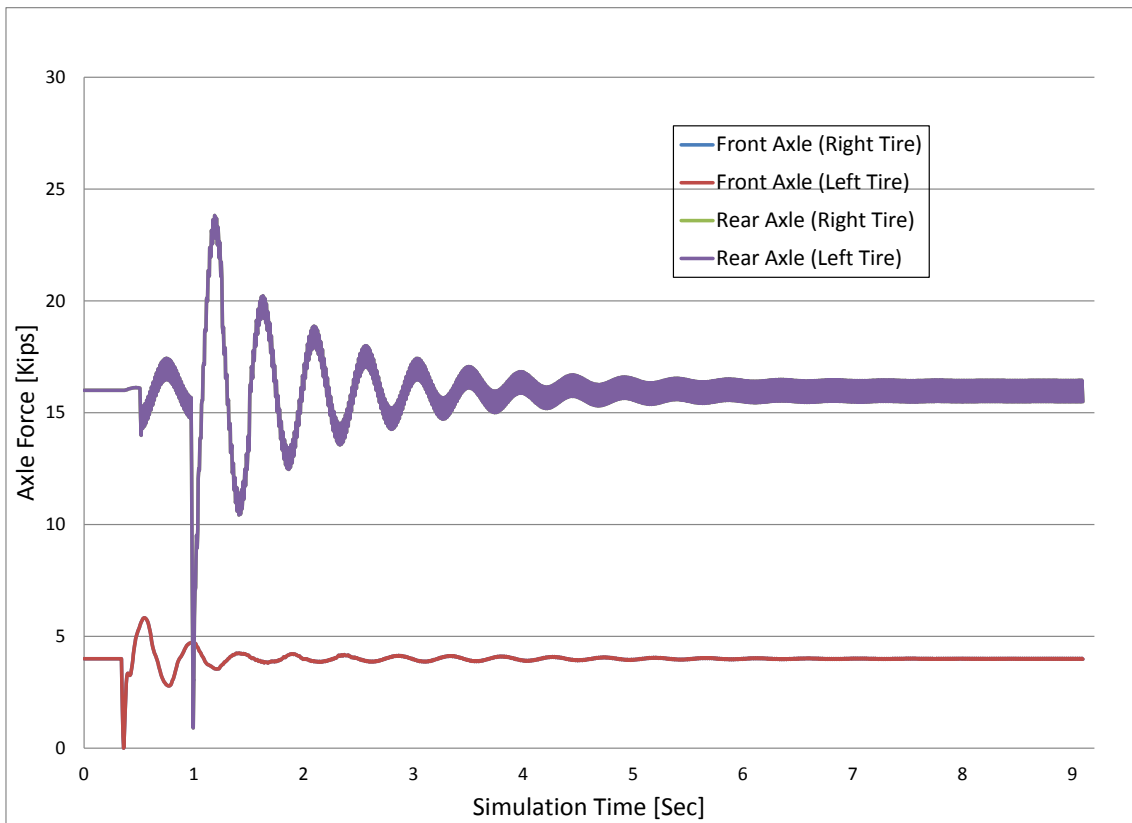


Figure 9. Time History of Different Tire Responses of H-20 Truck Traveling at 15 mph (1" Bump)

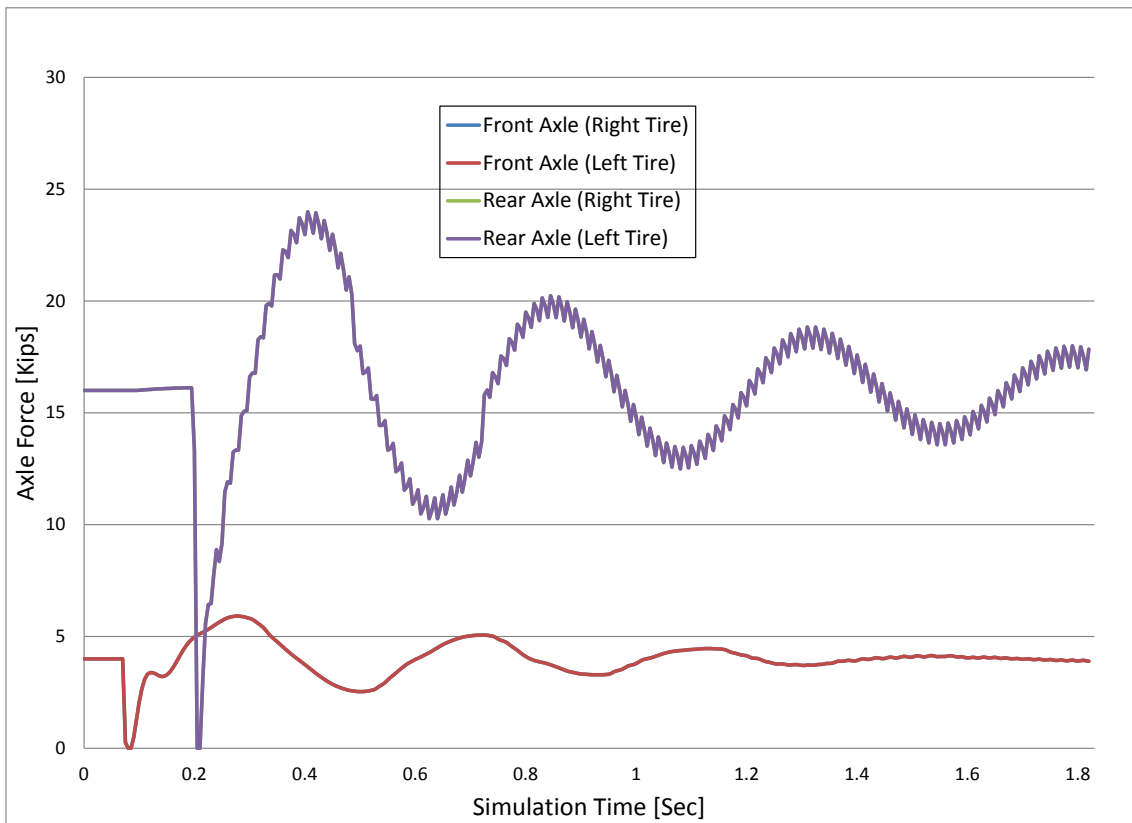


Figure 10. Time History of Different Tire Responses of H-20 Truck Traveling at 75 mph (1" Bump)

The tire impact factors of H-20 truck for front and rear axles when passing over the 1” bump has been shown in Figure 11. Slightly higher numbers for the rear axle can be seen in this graph which was also the case in the results from different road surface conditions.

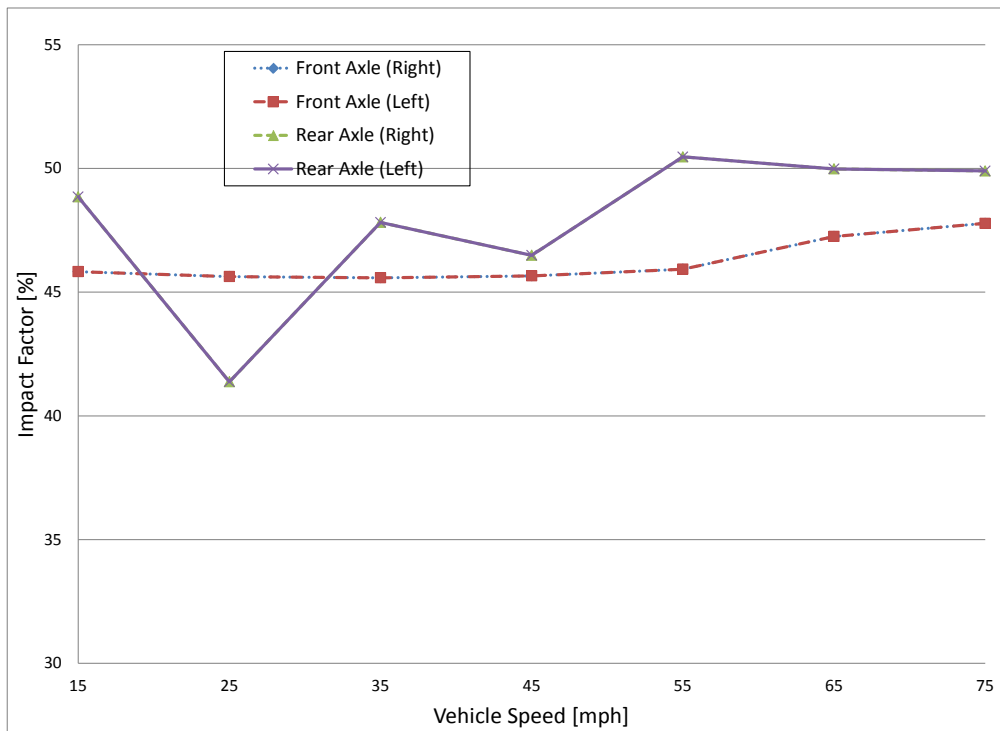


Figure 11. Tire Impact Factors of H-20 Truck for Front and Rear Axles (1” Bump)

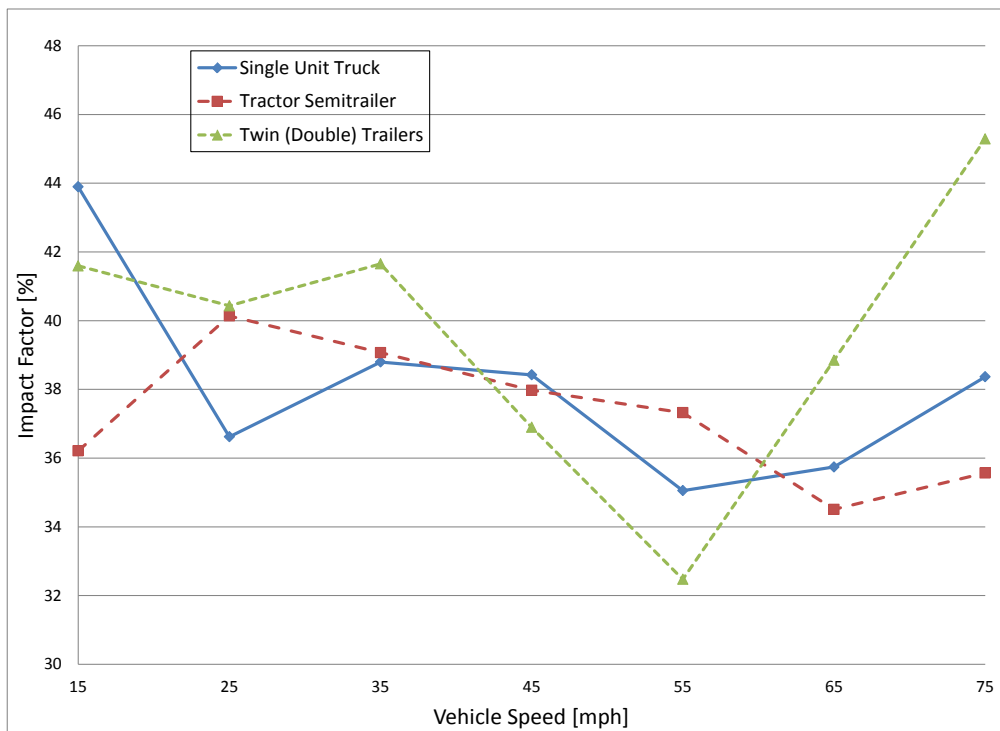


Figure 12. Tire Impact Factor of Different Vehicle Categories for the Selected Axle (1/2” Bump)

The averaged tire impact factor results of all vehicles, categorized in three groups of vehicles, when traveling over a 1/2", 1" and 2" bump have been shown in Figures 12 to 14. The results have been reported for the last axle of "Single Unit Trucks", last axle of "Tractor Semitrailers" and last axle of the first trailer of "LCVs".

These results show an increase in the impact factors as the height of the bump increases. The impact factors can be very high for the case of 2" bump which shows the strain that big potholes or height differentials between the surfaces can put on the roads.

One can also observe the same trend as the different road surface conditions in the previous section in these figures. In the cases of 1/2" and 1" bumps the LCVs result in higher impact factors but as the road surface condition gets worse (i.e. the case of 2" bump) the LCVs result in the lowest impact factors. All in all, the results from the LCVs are not that different from the other types of vehicles.

The results for the tire impact factors of the last axle of the first trailer of Long Combination Vehicles for all bump sizes have also been shown in Table 4. Extremely high values of impact factors can be seen in the case of the largest bump.

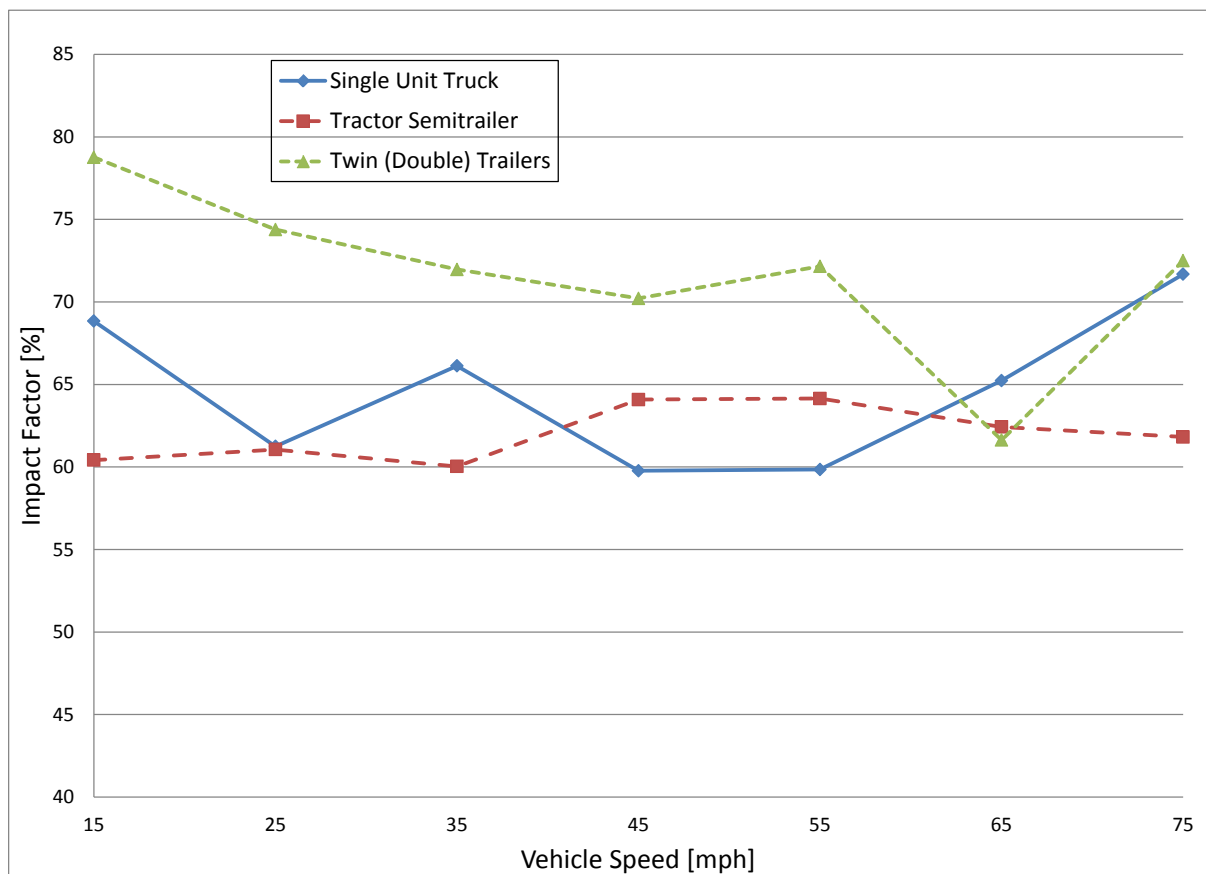


Figure 13. Tire Impact Factor of Different Vehicle Categories for the Selected Axle (1" Bump)

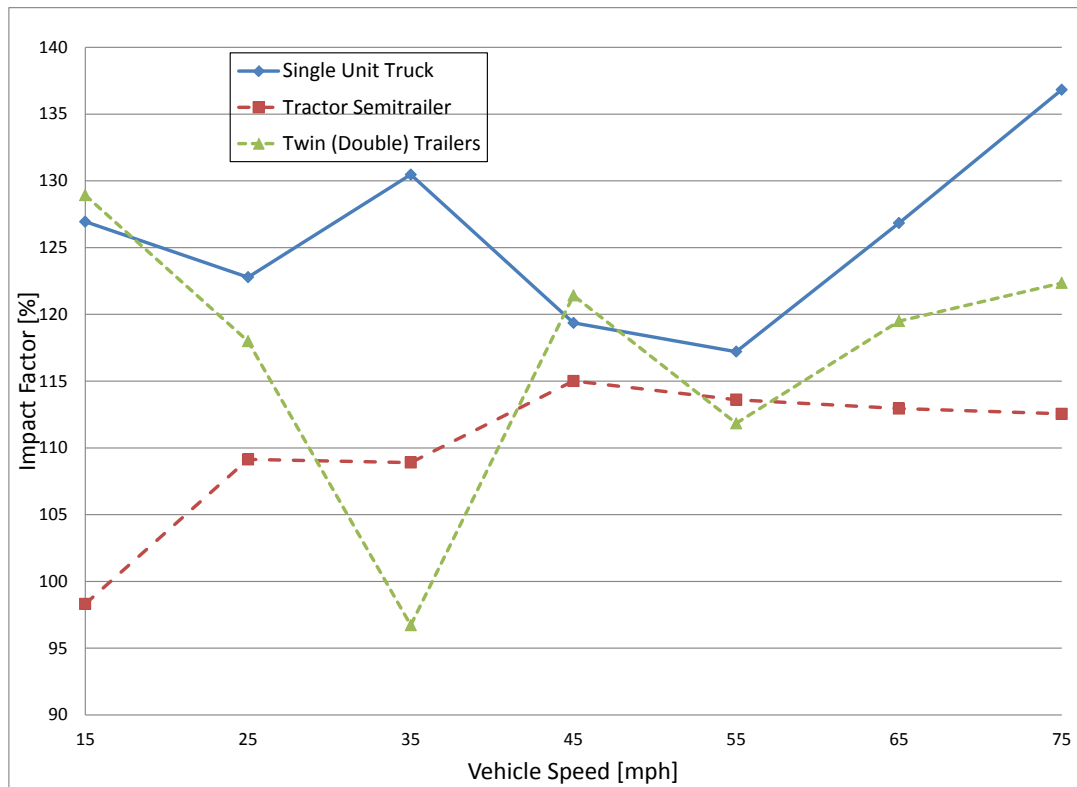


Figure 14. Tire Impact Factor of Different Vehicle Categories for the Selected Axle (2" Bump)

Table 4. Maximum Tire Impact Factors of the Long Combination Vehicles for the Selected Axle (All Bump Sizes)

Vehicle Speed [mph]	Tire Impact Factor [%]								
	7 Axle Rocky Mountain Double			8 Axle B-Train Double			9 Axle Turnpike Double		
	1/2 inch	1 inch	2 inches	1/2 inch	1 inch	2 inches	1/2 inch	1 inch	2 inches
15	38.9	79.8	136.1	39.3	71.3	109.3	46.5	85.2	141.4
25	44.2	77.5	125.6	34.4	60.3	96.1	42.7	85.4	132.3
35	37.6	79.7	102.0	41.7	67.3	86.8	45.7	69.0	101.4
45	28.9	68.4	116.6	49.5	65.0	116.3	32.3	77.3	131.4
55	33.6	68.7	108.1	34.0	66.2	117.4	29.8	81.7	110.1
65	37.8	55.2	116.7	43.7	61.9	115.9	35.0	67.9	125.9
75	52.0	75.4	129.8	42.6	61.6	103.6	41.2	80.5	133.6

#### 4. Conclusions

Two different sets of analysis were performed in order to understand the effects of Long Combination Vehicles (LCVs) on the road surfaces. Different road surface conditions ranging from “Very Good” to “Poor” were used in the first part to study the effects of different vehicle categories on the pavement. “Impact Factor” was used as an indicator of the vehicle response and it was observed that the values of impact factor could get very high in some cases. These values increased when the road surface condition got worse. The values of impact factors were higher for the lighter axles in most cases. The effect of vehicle speed on the vehicle responses was not easy

to comprehend. The LCVs had the highest values of impact factor among the three vehicle categories for the better surface conditions but they resulted in smaller impact factors in the relatively worse surface conditions.

In the second set of analysis, the effect of a single bump on the road was studied. Three different sizes for the bump were used ranging from 1/2" to 2". The results showed a good agreement with the conclusions made from the first set. As the bump size got higher the Impact factors got larger for all trucks and LCVs generated the highest values of impact factor in the cases of small bumps and smallest values in the case of largest bump.

In the future, the vehicle models of LCVs used in this paper can be used in the analysis of response of bridges as an important infrastructure on the roads to find answers to the question that whether current bridges are capable of carrying the loads of LCVs.

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