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Analysis of car and truck pavement impacts

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Objective

Using the Fourth Power Law, it has been estimated that a 5-axle tractor/ semi-trailer has a pavement impact equivalent to 9,600 passenger cars. In September 2018, FPInnovations was requested to comment on the pavement impacts of 5-axle tractor/ semi-trailers travelling on U.S. highways as compared with the impacts of passenger cars.

Background regarding 4th power law and ESALs

Starting in 1958, the American Association of State Highway Officials (AASHO) conducted a 2 year-long road test on the I-80 near Ottawa, Illinois during which vehicles made over 1.1M passes on six highway test loops containing sections of rigid (Portland Cement Concrete or PCC) and flexible (asphaltic concrete) pavements (an example is given in Figure 1). Trafficking was accelerated so that 2 years of trafficking could be extrapolated to the typical 20 year-life of flexible pavements. The purpose of the test was to study the performance of pavement structures of known thickness under moving loads of known magnitude and frequency. During the test, observations were regularly made of the pavement condition. On the pavement sections, measurements of roughness, rutting, cracking, patching repairs, and slab joint damage were gathered. The Road Test did not specifically evaluate passenger cars; however, it did traffic the test pavements with 2-axle trucks with single axle loads of 2000 lb.

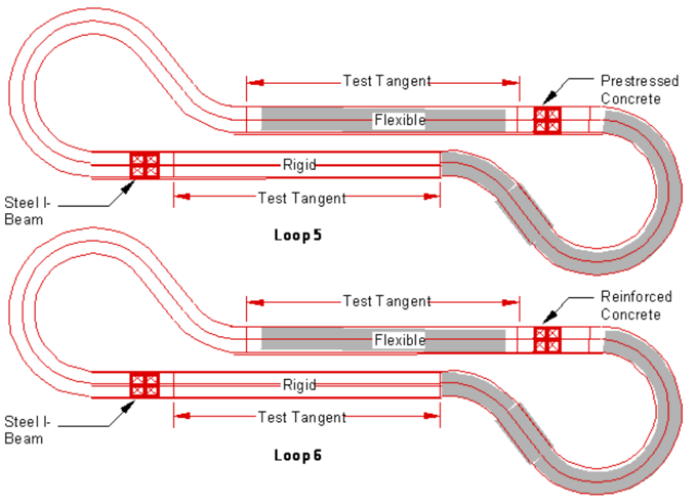

Figure 1. Arrangement of test loops 5 and 6 for the AASHO Road Test.

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The AASHO road test introduced many concepts in pavement engineering, including the load equivalency factor. Unsurprisingly, the heavier vehicles reduced the pavement service life in a much shorter time than light vehicles. The equivalent single axle load (ESAL) concept equates the pavement impact of any axle group with any loading the impact of a single axle with dual tires loaded to 18,000 lb. ESALs allow pavement designers to estimate the pavement impacts of a mixture of traffic types, having a wide variety of axle loadings and vehicle configurations. Because cars have a relatively small pavement impact, pavement design methods typically ignore the impacts of cars. The equivalent single axle load concept (ESAL) is by far the most widely accepted pavement concept in the world (Transportation Research Board. 2007).

The equation for calculating ESALs has the general form of:

$$\textbf{Axle group equivalency (ESALs)} = [\text{A x axle group load (lb)/ (18000 lb)}]^n$$

Where:

A = axle group coefficient
n = power

The power used in the ESAL formula can vary from about 1 to 6 because stronger pavements are less sensitive to load (Table 2), and some types of failure are less sensitive to load. For example, the power for predicting equivalency relative to rutting within the asphalt mat (non-structural rutting) is from 1 to 1.5, whereas the power is from 4 to 9 for subgrade rutting (structural rutting) equivalency, and from 4 to 5 for fatigue cracking equivalency. For rigid pavements, the power is 5 and the failure modes are structural rutting, concrete-related distress, and edge and joint deterioration. The Fourth Power relationship represents a typical value for the structural rutting and fatigue cracking range of power values in flexible pavements, and is commonly used to generally describe how axle load influences these important mechanisms of structural pavement failure.

According to the Washington Asphalt Pavement Association (2010) flexible pavements comprise about 95% of U.S. paved roads; that is, rigid pavements comprise 5% of U.S. paved roads. Although rigid pavements are a small component of the U.S. highway network, they were included in this discussion for completeness.

From the highway owner's perspective, the road users' experience has to be the most important factor to consider. Roughness is the most important factor that road users relate to road conditions; therefore, it has to be the most important factor to be considered. Cracking and rutting also contribute significantly to the pavement roughness over time and affect safety and long term pavement life.

Evaluation of the road impacts of passenger cars vs. 5-axle semi-trailers loaded to Inter-State weights using ESALs

Methodology

To estimate the relative impacts of passenger cars versus 5-axle tractor/ semi-trailers on a U.S. highway FPInnovations first calculated their ESALs using formulae from the AASHTO and then repeated the comparison using 5-axle truck factors published by the Asphalt Institute.

ESAL results for typical U.S. Highway flexible pavements. Table 1 summarizes the relative pavement impacts of cars and 5-axle semi-trailers at Inter-State axle load limits, on a typical, flexible (asphaltic concrete), U.S. highway structure (SN = 3, p_t = 2.5). The U.S. Environmental Protection Agency estimated in 2010 that an average passenger car weighs about 4000 lb. According to AASHTO (1993), two 2000 lb single axles generate 0.0004 ESALs on this type of pavement. This was taken to be equivalent to the impact from a 4000 lb passenger car. AASHTO (1993) estimates that an 80,000 lb 5-axle tractor/ semi-trailer generates 2.45 ESALs per pass. For this pavement, therefore, it could be said that every pass of a loaded 5-axle tractor/ semi-trailer theoretically causes as much pavement deterioration as 6123 cars.

Table 1. Comparison of ESALs for passenger cars and 5-axle tractor/ semi-trailers at Inter-State load limits, on a typical U.S. highway flexible pavement (SN = 3, p_t = 2.5)

BASELINE: 2-axle passenger car								
		2-axle car						
		steer	drive				GCW (tonnes)	1.82
Loaded	Axle Load (tonnes)	0.91	0.91				Tare Weight (tonnes)	1.82
	Equivalency (ESALs)	0.0002	0.0002				Payload (tonnes)	0.00
Unloaded (a)	Axle Load (tonnes)	0.91	0.91		EALs			
	Equivalency (ESALs)				0.0004			
US Interstate max loading 5-axle tractor semi-trailer (48' trailer)								
		tandem - tractor		Semi-trailer				
		steer	tandem	tandem			GCW (tonnes)	36.36
Loaded	Axle Load (tonnes)	5.45	15.45	15.45			Tare Weight (tonnes)	14.34
	Equivalency (ESALs)	0.23	1.11	1.11			Payload (tonnes)	22.02
Unloaded	Axle Load (tonnes)	5.14	6.00	3.20	EALs		No. of car passes equivalent to 1 truck pass	**6123**
	Equivalency (ESALs)				2.45			

NOTES: Equivalent axle loads for cars and tandem axle groups from 1993 AASHTO Guide for Design of Pavement Structure (SN=5, p_t = 2.0)
Axle factors are provided for each axle type, axle load (2 ton increments), and pavement structural number (SN).
Terminal Serviceability Index (Pt) for surveyed US states was about 2.25 (this is believed to be similar to Canadian highway maintenance practice)
ESALs exclude the pavement impacts of unloaded trucks (assumes all trucks are fully loaded)

Average ESAL Results for a Range of U.S. Highway flexible pavements. Table 2 summarizes the relative pavement impacts of cars, and 5-axle semi-trailers with average actual highway loadings, on six general U.S. highway classes. According to AASHTO (1993), a 2000 lb single axle generates from 0.0004 to 0.0008 ESALs for very strong to very weak highway pavements (Structural number SN = 6 to 1, respectively). Assuming the typical highway pavements were between SN values of 3 to 5, (Asphalt Institute 1989), representative equivalencies were estimated for passenger cars on all six classes of highway pavement (Table 2). Asphalt Institute (1989) lists truck factors (truck ESAL equivalencies) for a variety of pavement and truck classes. The average 5-axle tractor/ semi-trailer has an impact of from 0.97 to 1.25

ESALs per pass on flexible highway pavements. It can be seen that the 2.45 equivalency for the 5-axle tractor/ semi-trailer on the typical U.S. highway flexible pavement estimated in the first approximation (Table 1) is more than any of these values. This is because the values in Table 2 were derived from actual vehicle weights measured at agency weigh stations that would have ranged from unloaded to lightly loaded to slightly overloaded. The average truck load was less than the 80,000 lb limit and, therefore, generated considerably fewer ESALs, on average. For the given assumptions, Asphalt Institute estimates that one pass of a 5-axle tractor/ semi-trailer theoretically causes as much highway asphalt pavement deterioration as 1750 to 2925 passes by a car. Asphalt Institute notes that Truck Factors can vary by 50% or more for specific conditions.

Table 2. Comparison of vehicle equivalencies based on passenger car ESALs and truck factors for 5-axle tractor/ semi-trailer traffic

Vehicle Type	Truck Factors[2]					
	Rural Systems			Urban Systems		
	Inter-State	Other Principal	Minor Arterial	Inter-State	Other freeways	Other Principal
Passenger car (4000 lb)	0.0005	0.0006	0.0006	0.0004	0.0004	0.0005
5-axle semi	1.09	1.25	1.05	1.07	1.17	0.97
5-axle / passenger car	**2180**	**2083**	**1750**	**2675**	**2925**	**1940**

2. Individual situations may differ from these average values by 50% or more

ESAL results for typical U.S. Highway rigid pavements. Table 3 summarizes the relative pavement impacts of cars and 5-axle semi-trailers at Inter-State axle load limits, on a typical, rigid (Portland Cement Concrete), U.S. highway structure (D = 11”, p_t = 2.5). According to AASHTO (1993), two 2000 lb single axles generate 0.0004 ESALs on this type of pavement; this was taken to be equivalent to the impact from a 4000 lb passenger car. AASHTO (1993) estimates that an 80,000 lb 5-axle tractor/ semi-trailer generates 4.26 ESALs per pass. For this pavement, therefore, it could be said that every pass of a 5-axle tractor/ semi-trailer theoretically causes as much pavement deterioration as 10,643 cars.

Table 3. Comparison of ESALs for passenger cars and 5-axle tractor/ semi-trailers at Inter-State load limits, on a typical U.S. highway rigid pavement (D = 11", pt = 2.5)

BASELINE: 2-axle passenger car									
		2-axle car							
		steer	drive					GCW (tonnes)	1.82
Loaded	Axle Load (tonnes)	0.91	0.91					Tare Weight (tonnes)	1.82
	Equivalency (ESALs)	0.0002	0.0002					Payload (tonnes)	0.00
Unloaded (a)	Axle Load (tonnes)	0.91	0.91		EALs				
	Equivalency (ESALs)				**0.0004**				
US Interstate max loading 5-axle tractor semi-trailer (48' trailer)									
		tandem - tractor		Semi-trailer					
		steer	tandem	tandem				GCW (tonnes)	36.36
Loaded	Axle Load (tonnes)	5.45	15.45	15.45				Tare Weight (tonnes)	14.34
	Equivalency (ESALs)	0.34	1.96	1.96				Payload (tonnes)	22.02
Unloaded	Axle Load (tonnes)	5.14	6.00	3.20	EALs			No. of car passes equivalent to 1 truck pass	**10,643**
	Equivalency (ESALs)				**4.26**				

a) *Equivalent axle loads from 1993 AASHTO Guide for Design of Pavement Structure (D=11, p_t = 2.5 (Tables D.13 - D.14))*
b) *Axle factors are provided for each axle type, axle load (2 ton increments), and slab thickness.*
c) *Terminal Serviceability Index (Pt) for surveyed US states was about 2.25 (this is believed to be similar to Canadian highway maintenance practice)*
d) *ESALs exclude the pavement impacts of unloaded trucks (assumes all trucks are fully loaded)*

Limitations of the ESAL method

A limitation of the AASHTO pavement design's ESAL calculation method is that the accuracy of the pavement design relies upon the accuracy of the estimates of traffic composition and vehicle loadings (AASHTO 1993). That is, the ability of the 4th power law to accurately quantify general, long term, pavement impacts from cars vs trucks is very limited due to the wide variation in vehicle configurations and loadings seen in real life.

A second and more important limitation of the ESAL concept (and truck factors) is that it is based upon dated and specific conditions tested almost 70 years ago at one location. They reflect the pavement, vehicle and tire types, weather, and soil conditions of the Road Test. Obviously, many things have changed from 70 years ago (e.g., pavement materials; pavement designs; truck loadings; tire types, sizes, and inflation pressures; travel speeds; weather patterns). Application of ESALs in other than the test location introduces some unknown amount of error because climate, pavement age and condition, and soil type and condition, will be likely be different. AASHTO (1993) included factors to account for different soils and climate. Over time, pavement designers have found that pavement performance has been less than predicted using the ESAL method and attribute this, in large part, to the inability of the ESAL method to account for variations in soil and climate (Transportation Research Board 2007). Although some road owners continue to use ESALs for pavement design, they generally recognize that ESALs are not transferable from one jurisdiction to another. Some road owners have their own way to calculate ESALs based on their structures, climates, and their preferred weighting of damage mechanisms.

A third limitation of ESALs is that they don't account for tire parameters (type, size, inflation). The original tests were conducted with bias ply tires, which have now been completely replaced with radial tires. Tire parameters have been found to strongly influence near-surface pavement deterioration, notably cracking.

A fourth limitation of the ESAL method for this specific comparison is that it does not specifically consider light passenger vehicles (passenger cars, motorcycles, pick-up trucks, etc.). These vehicles have light axle loads, and their tires and suspensions provide for less dynamic loading to a pavement than the relatively stiffer truck tires and suspensions. Experience has shown that light passenger vehicles can significantly impact pavement condition but at higher numbers than commercial trucks.

Mechanistic Empirical Estimates of Relative Pavement Impacts from Cars and Trucks

For the numerous reasons listed in the Background section of this report, FPInnovations believes that ESALs and truck factors ***do not provide*** an accurate and valid estimate of the relative impact of passenger cars to 5-axle commercial trucks. Accordingly, FPInnovations conducted an assessment of long term pavement impacts using a mechanistic empirical approach and a pavement design program called WinJULEA. This type of pavement modeling has been found to more accurately assess pavement performance than ESALs under a wide variety of conditions and over long periods of trafficking. This approach uses mechanistic empirical estimates of the properties of key factors in its estimation of pavement impacts, including pavement characteristics and condition, unbound pavement material physical and mechanical properties, pavement layer thicknesses, subgrade soil bearing capacity (as a function of temperature and moisture conditions), tire contact pressure (as function of tire size and inflation and loading), and vehicle loading (as a function of wheel load, and the spacing of axles and wheels).

Using WinJULEA, one can calculate instantaneous strains at key locations in a pavement structure. Using well-accepted strain-based equations from the Asphalt Institute (Huang 2004), the number of cycles to cause a failed condition in structural rutting or in fatigue cracking can be predicted (i.e., Asphalt Institute specifies failure as a ½" deep surface rut or fatigue cracking over 10% of the wheel path). Based on the number of vehicle passes to cause a failed condition in the pavement, the relative pavement impact of the two subject vehicles can be compared with confidence.

Pavement Modeling Inputs. FPInnovations utilized WinJULEA, a layered elastic pavement analysis software based on the Burmister theory, to model a typical U.S. flexible asphalt highway pavement. The typical highway pavement structure was based on a definition provided in Mahoney (1988). The pavement was taken to be a moderate strength 6" (150 mm)-thick asphalt mat, over a 6" (150 mm)-thick granular base course, over an 18" (450 mm)-thick subbase course, founded on a silty Sand subgrade. The passenger cars were assumed to weigh 4000 lb, on average, and the 5-axle trucks were assumed to weigh 80,000 lb (the Inter-State highway load limit).

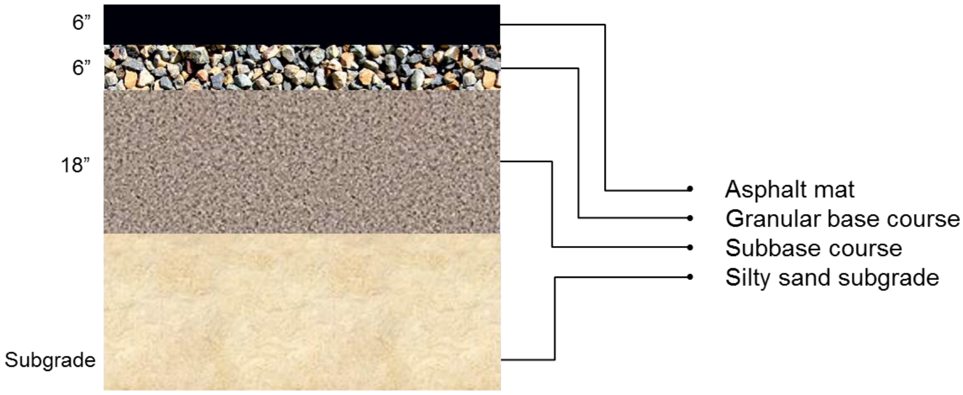

Figure 2. Cross-section of representative U.S. highway used for WinJULEA analysis.

Obviously, these parameters will vary from highway to highway, and over time. The sensitivity of the results was tested, therefore, by varying three key parameters: asphalt layer stiffness, subgrade soil stiffness, and 5-axle truck loading. The asphalt layer stiffness was varied from 150,000 psi (1035 MPa) to 362,000 psi (2500 MPa) to consider a moderate strength, lightly cracked, average condition and a new, un-cracked, strong highway pavement, respectively. The subgrade soil stiffness was varied from 29,000 psi (200 MPa) to 14,065 psi (97 MPa) to consider both a good quality subgrade material and a moderately weak subgrade soil. Material properties for the various pavement layers were estimated from past analyses and from the MEPDG (Mechanistic Empirical Pavement Design Guide, 2000). Pavement responses to a standard 18,000 lb single truck axle, a passenger car, and a 5-axle tractor/ semi-trailer were estimated. The 5-axle truck loading was evaluated at both the 80,000 lb Inter-State load limit and at 84,000 lb to reflect a moderately (5%) overloaded condition.

Four pavements and three loadings were evaluated, as follows:

	moderately worn asphalt	new, strong asphalt
good quality subgrade	passenger car, fully loaded 5-axle, 5% overload 5-axle	passenger car, fully loaded 5-axle, 5% overload 5-axle
moderately weak subgrade	passenger car, fully loaded 5-axle, 5% overload 5-axle	passenger car, fully loaded 5-axle, 5% overload 5-axle

Highway Pavement Modeling Results

Scenario 1 – Moderately worn asphalt/good quality subgrade. In the first scenario, featuring a moderately worn asphalt layer and a good quality subgrade, the pavement was predicted to fail in fatigue cracking before failing by structural rutting, for all vehicle loadings tested (Table 3). This result was expected given that highway is constructed to be a relatively strong pavement. The pavement was predicted to fail in fatigue cracking after 272,600 passes of an 80,000 lb 5-axle truck or after 77,724,200 passes of a 4,000 lb car. The relative impact of 5-axle trucks to cars, therefore, is predicted to be one 5-axle truck pass to 285 passenger car passes (1:285).

The effect of truck overloading also was considered. With a 5% overload (84,000 GVW), 5-axle trucks are predicted to create a failed condition in the pavement after 242,800 passes. This means that the 5% overloading increased the rate of wear and tear in the pavement by about 11%, to a ratio of one truck pass to 320 car passes (1:320).

Scenario 2 – New strong asphalt/good quality subgrade. In the second scenario, featuring a new, strong asphalt layer and a good quality subgrade, the pavement was predicted to fail in fatigue cracking after 645,500 passes of an 80,000 lb 5-axle truck (Table 3). This is considerably more than in Scenario 1 and reflects how much better a new, strong, un-cracked, asphalt layer can resist fatigue cracking. The pavement was predicted to fail in fatigue cracking after 196,915,100 passes of a 4,000 lb car. The relative impact of 5-axle trucks to cars, therefore, is predicted to be one 5-axle truck pass to 305 passenger car passes (1:305).

At a 5% overload (84,000 GVW), the 5-axle truck was predicted to create a failed condition in the pavement after 576,200 passes. This means that the 5% overloading increased the rate of wear and tear in this stronger pavement by about 11%, to a ratio of one truck pass to 342 car passes (1:342).

Scenario 3 – Moderately worn asphalt/moderately weak subgrade. In the third scenario, featuring a moderately worn asphalt layer and a weak subgrade, the pavement was predicted to fail in fatigue cracking before failing in structural rutting, for all of the vehicle loadings (Table 3). This is comparable to the results of Scenario 1 and illustrate that the relatively thick subbase layer was effective at limiting the impact of the weak subgrade on both cracking and rutting. This is reasonable given that highway pavement designs are intended to survive on the wide variety of subgrades found in the USA. The pavement was predicted to fail in fatigue cracking after 274,800 passes of an 80,000 lb 5-axle truck or after 78,305,300 passes of a 4,000 lb car. The relative impact of 5-axle trucks to cars, therefore, is predicted to be one 5-axle truck pass to 285 passenger car passes (1:285). This is the same ratio of relative pavement wear that was predicted in Scenario 1.

The 5% overloaded 5-axle truck was predicted to create a failed condition in the pavement after 244,800 passes. This means that the 5% overloading increased the rate of wear and tear in the pavement by about 11%, to a ratio of one truck pass to 320 car passes (1:320).

Scenario 4 – New strong asphalt/moderately weak subgrade. In the fourth scenario, featuring a new, strong asphalt layer and a weak subgrade, the pavement was predicted to fail in fatigue cracking after 621,300 passes of an 80,000 lb 5-axle truck or after 190,142,400 passes of a 4,000 lb car (Table 3). The relative impact of 5-axle trucks to cars, therefore, is one 5-axle truck pass to 306 passenger car passes (1:306). This is the virtually the same relative ratio of relative pavement wear that was predicted in Scenario 2.

The 5% overloaded 5-axle truck was predicted to create a failed condition in the pavement after 554,000 passes. This means that the 5% overloading increased the rate of wear and tear in the pavement by about 11%, to a ratio of one truck pass to 343 car passes (1:343).

Table 4 summarizes the results from the highway pavement modeling results.

Table 4. Comparison of long term U.S. highway pavement impacts of passenger cars and 5-axle trucks

Scenario	Configuration	Axle group	Mass (pounds)	Estimated Cycles to Failure at Critical Strain: Fatigue Cracking (cycles)	Estimated Cycles to Failure at Critical Strain: Rutting (cycles)	Governing Failure Mode: Cycles to failure	Governing Failure Mode: Mode	Comparison to failure cycles of a car
Mr AC= 1035 MPa & Mr Subgrade = 97 MPa		steer	2002	155,448,404	467,226,350,131	155,448,404	Fatigue cracking	
		drive	2002	155,448,404	467,226,350,131	155,448,404	Fatigue cracking	
	car		4004			77,724,202	Fatigue cracking	**1**
		steer	12000	675,851	155,232,178	675,851	Fatigue cracking	
		tandem	34000	1,827,691	720,391,656	1,827,691	Fatigue cracking	
		tandem	34000	1,827,691	720,391,656	1,827,691	Fatigue cracking	
	5-axle semi		80000			272,615.51	Fatigue cracking	**285**
		steer	12000	675,851	155,232,178	675,851	Fatigue cracking	
		tandem	36000	1,515,888	558,334,903	1,515,888	Fatigue cracking	
		tandem	36000	1,515,888	558,334,903	1,515,888	Fatigue cracking	
	5-axle semi (5% overload)		84000			242,817	Fatigue cracking	**320**
Mr AC= 2500 MPa & Mr Subgrade = 97 MPa		steer	2002	393,830,336	938,503,342,379	393,830,336	Fatigue cracking	
		drive	2002	393,830,336	938,503,342,379	393,830,336	Fatigue cracking	
	car		4004			196,915,168	Fatigue cracking	**1**
		steer	12000	1,577,806	309,967,144	1,577,806	Fatigue cracking	
		tandem	34000	4,370,418	1,441,928,020	4,370,418	Fatigue cracking	
		tandem	34000	4,370,418	1,441,928,020	4,370,418	Fatigue cracking	
	5-axle semi		80000			645,563	Fatigue cracking	**305**
		steer	12000	1,577,806	309,967,144	1,577,806	Fatigue cracking	
		tandem	36000	3,631,510	1,119,602,615	3,631,510	Fatigue cracking	
		tandem	36000	3,631,510	1,119,602,615	3,631,510	Fatigue cracking	
	5-axle semi (5% overload)		84000			576,282	Fatigue cracking	**342**
Mr AC= 1035 MPa & Mr Subgrade = 40 MPa		steer	2002	156,610,769	59296183819	156,610,769	Fatigue cracking	
		drive	2002	156,610,769	59,296,183,819	156,610,769	Fatigue cracking	
	car		4004			78,305,384	Fatigue cracking	**1**
		steer	12000	681,664	19,728,323	681,664	Fatigue cracking	
		tandem	34000	1,842,627	91,645,270	1,842,627	Fatigue cracking	
		tandem	34000	1,842,627	91,645,270	1,842,627	Fatigue cracking	
	5-axle semi		80000			274,891	Fatigue cracking	**285**
		steer	12000	681,664	19,728,323	681,664	Fatigue cracking	
		tandem	36000	1,528,386	71,019,496	1,528,386	Fatigue cracking	
		tandem	36000	1,528,386	71,019,496	1,528,386	Fatigue cracking	
	5-axle semi (5% overload)		84000			244,850	Fatigue cracking	**320**
Mr AC= 2500 MPa & Mr Subgrade = 40 MPa		steer	2002	380,284,993	118,534,653,279	380,284,993	Fatigue cracking	
		drive	2002	380,284,993	118,534,653,279	380,284,993	Fatigue cracking	
	car		4004			190,142,496	Fatigue cracking	**1**
		steer	12000	1,517,421	39,189,266	1,517,421	Fatigue cracking	
		tandem	34000	4,208,692	182,401,909	4,208,692	Fatigue cracking	
		tandem	34000	4,208,692	182,401,909	4,208,692	Fatigue cracking	
	5-axle semi		80000			621,339	Fatigue cracking	**306**
		steer	12000	1,517,421	39,189,266	1,517,421	Fatigue cracking	
		tandem	36000	3,491,030	141,367,895	3,491,030	Fatigue cracking	
		tandem	36000	3,491,030	141,367,895	3,491,030	Fatigue cracking	
	5-axle semi (5% overload)		84000			554,076	Fatigue cracking	**343**

Conclusions

The fourth power law is a trend that was found in the pavement deterioration data from the AASHO Road Test and became the basis for creating load equivalencies. Load equivalencies or ESALs are a widely accepted concept for estimating pavement impacts of a mixture of truck configurations and loadings. ESAL relations are used by many agencies to approximate the impacts of large numbers of trucks over the service life of a pavement. By their nature, ESALs are general relations of pavement impacts and cannot accurately reflect specific parameters of tires, climate, pavement design and condition, drainage, etc. Further, cars and light vehicles were not specifically tested in the AASHO Road Test. Use of 2000 lb truck axle impacts to estimate passenger car impacts is questionable because of the differences in suspension and tire characteristics.

Given published data from the Asphalt Institute and AASHTO, ESALs were approximated for trucks versus cars on both flexible and rigid U.S. highway pavements. The ESALs for flexible highway pavements have a relation similar to the 4^{th} Power Rule, whereas ESALs for rigid pavements are calculated with a power of 5. AASHTO (1993) estimates that a 5-axle tractor semi-trailer loaded to 80,000 lb can cause as much flexible pavement deterioration as 6,123 passes of a typical car (1:6123). Data from actual highway traffic data, however, leads to the prediction that one pass of a 5-axle tractor/ semi-trailer theoretically causes as much flexible pavement deterioration as 1750 to 2925 passes by a car, depending on highway class (1:1750 to 1:2925). (Asphalt Institute notes that these values can vary by ±50% or more for specific conditions.) For a typical rigid pavement structure, data from actual highway traffic data leads to the prediction that that one pass of a 5-axle tractor/ semi-trailer theoretically causes as much deterioration as 10,643 passes by a car (1:10,643). While this estimate is similar to the originally theorized (1:9,600) ratio, it is for rigid pavements which represent no more than 5% of the U.S. highway network.

A more accurate way to compare vehicle impacts to a specific pavement is to use a mechanistic empirical analysis, with vehicle and site-specific inputs. FPInnovations' conducted a mechanistic empirical pavement analysis of a typical U.S. flexible highway pavement using WinJULEA layered elastic analysis. The analysis considered four scenarios of pavement condition (average worn asphalt surface on a strong and a weak subgrade soil; new, strong, asphalt surface on a strong and a weak subgrade soil). The modeling predicted that relatively strong Inter-State highway pavements are likely to reach a fatigue-cracked failure condition faster than a structural-rutted failure condition. This was an expected outcome and would hold for a wide variety of strong highway pavements.

Passenger cars were predicted to create much less pavement deterioration (rutting and fatigue cracking) per pass than do 5-axle commercial trucks but not of the magnitude estimated using the Fourth Power Law (e.g., 1:6100). For the pavement scenarios featuring a highway pavement with an average worn asphalt condition, the relative wear rate for the 80,000 lb 5-axle tractor/ semi-trailer was estimated to be 285 times that of a typical passenger car (1:285). When the 5-axle truck was moderately overloaded, the relative wear ratio increased to 320 passenger cars (1:320). No estimates were made of 5-axle trucks loaded to less than 80,000 lb, however, these would have produced even smaller ratios.

For the pavement scenarios featuring a flexible highway pavement with a new, strong asphalt condition, the relative wear rate for the 80,000 lb 5-axle tractor/ semi-trailer was estimated to be 305 or 306 times that of a typical passenger car (1:305, 1:306). When the 5-axle truck was moderately overloaded, the relative wear ratio increased to 342 or 343 passenger cars (1:342 / 1:343).

While this analysis is not exhaustive in its consideration of highway structures, given the limited variability observed in scenarios evaluated, FPInnovations believes that the results give a reliable approximation of the relative impact of passenger cars and 5-axle trucks loaded to Inter-State load limits on U.S. highway pavements. Nor were the results overly sensitive to a moderate degree of truck overloading.

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