Pavement Performance Considerations
For Heavy Traffic Loads

Buses; Refuse Trucks; Concrete Trucks; Fire Trucks

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Scope. The purpose of this paper is to identify and quantify the more significant, heavier vehicular loads to which the city's streets are subjected, and provide a means of visualizing and understanding how the various loads affect the service life of the city's pavement infrastructure – particularly the local access streets.

Background. The development of hard surfaces for paths and roads was borne of the necessity to accommodate and enhance mobility during all climatic conditions. Over the years, practitioners have experimented with many ways to create all-weather roads. Early methods utilized stones, branches and logs, whereas modern methods rely primarily on the use of naturally occurring and processed mineral aggregates, asphalt concrete, and cement concrete – either separately or in combination – to produce smooth, functional, long-lasting surfaces.

Over the years, the methodology for designing suitable pavement structures has evolved from trial and error to the use of computers employing sophisticated numerical methods. The goal was and is to produce a roadway surface that is suitably smooth, and upon which people can travel with a reasonable expectation of being able to do so safely, under all environmental conditions.

A number of factors must be considered when designing modern pavement structures, three of which include: (1) the ability of the underlying soils to support loads, (2) the type and availability of construction materials, and (3) the degree of loading to be accommodated – the traffic loads.

Traffic loading refers not only to the magnitude of the loads – the weight that is being applied to the pavement section – but also the nature or arrangement of the applied loads, and the frequency of the loading, that is, *how many times* that weight is applied, or the *axle load accumulation*. As an example, the design of the frame for a semi-trailer must consider two basic elements: (1) the frame must be strong enough to support the load that the trailer is intended to carry, and (2) the frame must be tough enough to resist the repeated stress fluctuations resulting from the bouncing action as the vehicle travels down the road; that is, the frame must also be fatigue resistant.

Likewise, it is intuitive that the useful life of a roadway section will similarly be affected by the number of applied loadings.

During the late 1950's, the American Association of State Highway Officials (AASHO) – now called the American Association of State Highway and Transportation Officials (AASHTO) – undertook an extensive research effort, called the AASHO Road Test, to "...establish relationships showing how performance of pavements is influenced by structural design, represented by component thicknesses of pavement structure, and loading, represented by the magnitude and frequency of axle loads, for both rigid and flexible pavements of conventional design."

The AASHO Road Test showed that the damaging effect of the passage of an axle of any mass – load – can be represented by a number of 18,000 pound equivalent single axle loads or ESALs. For example, one application of a 12,000 pound single axle was found to cause damage equal to approximately 0.23 applications of an 18,000 pound single axle load; or, conversely about four applications of a 12,000 pound single axle were required to cause the same damage (or reduction in serviceability) as one application of an 18,000 pound single axle.

Further analysis of the AASHO Road Test resulted in the realization that the amount of damage inflicted on a pavement structure by the application of varying axle loads is *non-linear*. That is, the reduction in pavement serviceability index (PSI) – the "damage" to the roadway – for a load that is twice as large as an initial load is far greater than two times that of the initial load. In fact, the damage is exponential; as a rule-of-thumb, roughly the fourth power. So, doubling a load (for a given wheel and axle configuration) will inflict about **sixteen times** the amount of "damage" (reduction in PSI) on a pavement structure. It must be understood that this is an approximation, but that it is also reflective of the generalized relationship observed in the test data.

<u>Load Equivalency Factors.</u> Subsequent work has resulted in the creation of tabular data that are utilized by pavement design engineers to rationally transform traffic number forecasts into the predicted number of ESALs a pavement structure must accommodate over the chosen or designated analysis period. The predicted ESAL count is then used in conjunction with other pertinent information to design a suitable pavement section.

To express varying axle loads in terms of a single design parameter, axle load equivalency factors – LEFs – were developed. It is these numbers that are shown in the various tables. They relate the potential for reduction in PSI for a given load to the potential for reduction in PSI for one ESAL. For example, a loading – load "A" – represented by an LEF of .05 imparts only 5% of the "damage" to a pavement structure as that of a loading – load "B" – represented by an LEF of 1.00 – one ESAL. Conversely, it takes approximately 20 repetitions (1÷0.05) of load "A" to equal the amount of damage imparted by one repetition of load "B".

The total amount of traffic expected over the analysis period is calculated by taking the current traffic volume, applying an appropriate growth model – often an assumed annual growth rate – and then summing up all the traffic over the analysis period. Once the total number of vehicles is known, the mix of traffic – percentage of heavy and light trucks, buses, cars, etc. – is applied, and the total number of each vehicle type is calculated. Then, knowing the axle weights, number of axles, and axle arrangement (single, dual, triple) for each vehicle type, the ESALs over the analysis period are calculated by applying and summing the appropriate LEFs from the table for each vehicle type.

More recent analysis of the AASHO Road Test Data by the Trucking Research Institute (TRI) suggests that LEFs for both flexible and rigid pavements should be larger for lighter loaded axles and smaller for heavier loaded axles as compared to AASHTO LEFs. This means that the fourth power relationship for reduction in PSI may be less – about the 3.5 power, using the TRI numbers.

There are yet other factors – beyond the scope of this paper – that affect the overall relationship of load magnitude, arrangement and repetition to pavement damage. Nonetheless, the conclusion remains unchanged:

> *For an equal number of applications*, heavier loads produce appreciably more damage to a roadway pavement than do lighter loads.

Or, put another way:

> *For a given period of time,* higher numbers of ESALs produce appreciably more damage to a roadway pavement than do lower numbers of ESALs.

A corollary to the above would be:

> For a given pavement section, an increase in loading applications beyond the assumed design loading model will hasten the deterioration rate of the pavement, thus causing the pavement to reach its terminal serviceability index prematurely.

Vehicle Load Factor. For any vehicle, when the loads on the individual axles or duals/triples are known, then the sum of all the LEFs for each axle or axle group will yield the total number of ESALs for that vehicle. This is also sometimes called the Truck Factor in other literature. For the purposes of this paper, however, the total number of ESALs for any vehicle will be referred to as the Vehicle Load Factor – VLF.

Sample Vehicle Load Factors. Using the tables from Appendix D of the 1993 AASHTO Guide for Design of Pavement Structures, and the actual axle weight data for the indicated vehicles, the following VLFs are calculated for various vehicle configurations found on City of Spokane streets, for average conditions:

Vehicle	VLF	Passenger Cars Equivalent
Passenger car (assumed base line)	0.0004	1
Central pre-mix 7yd^3 concrete truck	1.84	4,600

Central pre-mix 10yd^3 concrete truck		2.03	5,100
STA Boyertown streetcar:	empty	1.35	3,400
	100% full	2.76	6,900
	150% full	3.80	9,500
STA bus, GMC T8H603:	empty	1.15	2,900
	100% full	2.98	7,500
	150% full	3.89	9,700
STA bus, FLXIBLE 870:	empty	1.25	3,100
	100% full	3.49	8,700
	150% full	5.55	13,900
STA bus, MAN articulated – SG310:	empty	0.81	2,000
	100% full	2.45	6,100
	150% full	4.59	11,500
City garbage truck: Front loader	empty	n/a	n/a
	full	5.48	13,700
City garbage truck: Rolloff	empty	1.91	4,800
	full	5.48	13,700
City garbage truck: traditional rear loader	empty	n/a	n/a
	full	3.37	8,400
City garbage truck: residential curbside	empty	2.01	5,000
	full	4.71	11,800
City fire truck: older engines	full	0.21	500
City fire truck: newer engines	full	0.68	1,700
City fire truck: downtown ladder	full	4.37	10,900
City fire truck: new tillered ladder	full	3.45	8,600
City fire truck: L-2 (due 2005)	full	6.87	17,200
	Average	2.74	6,800

In terms of absolute effect (highest VLF) for any single load application, it can be seen that empty buses rank below the average; full buses and garbage trucks rank above average; and fire trucks are mixed, some ranking well below average, others a bit above average about like the buses and garbage trucks; and one (the proposed new fire truck) ranking well above average.

Cumulative Impact. Understanding the one-time impact of these vehicles is only half the story; the overall impact must consider the number of times these vehicles use the streets during the pavement analysis period.

In the case of passenger cars, cumulative impact is essentially moot because of the extremely small VLF associated with passenger cars – pavement deterioration in this case is primarily associated with environmental effects, or perhaps the application of unforeseen low frequency, but very massive loads.

> Consider that during a typical 20-year analysis period, some blocks of residential streets may see fewer than one million passenger cars – around 100 per day – which would equate to only 400 ESALs during the analysis period. Other blocks might see more, depending on the geometric layout of the roadway grid for accessing the arterial network. **In contrast, it is not uncommon to design an average arterial street for millions of ESALs during its analysis period, and tens of millions for busier arterials and highways.**

As for *garbage trucks*, for the most part we would consider that they use a local access street perhaps once a week. For *fire trucks* the usage might even be less than the garbage trucks. For *buses*, the usage is a function of the bus route and schedule. As an example, an inspection of STA's various bus schedules indicates that bus trips vary from fewer than twenty to more than sixty per day (in one direction), depending on the route.

Of course for buses, garbage trucks and fire trucks, the nearer to their main functional nodes, the more concentrated is their traffic, and thus their effect on the roadway system. As an example, for buses we would be interested in the bus operations facility on west Broadway Avenue; the downtown transit plaza; and the various park and ride locations. For garbage trucks we would be concerned with the waste-to-energy plant; the transfer stations; and the Solid Waste yards near Perry Street and Madelia Avenue.

According to STA the Monroe Street Bridge and Monroe Street, proper immediately north and south of the bridge, which feed the downtown bus plaza were accommodating in the neighborhood of ***600 buses per day*** at the time the bridge was shut down to bus traffic just prior to the bridge reconstruction project. The data in the above table suggest that this level of bus traffic would be roughly equivalent to **1.2 MILLION** passenger cars **EVERY DAY**, in terms of the reduction in serviceability index imparted to the pavement structure!

> **OBSERVATION: on a trip-for-trip basis, bus loads are less significant than those for most garbage trucks and fire trucks. However, for those streets utilized by the transit system, when taking trip frequency into account, buses account for perhaps THE most significant loading on the city's streets (see the example, below) – certainly so for local access streets.**

As stated in the Washington State Department of Transportation *Pavement Guide Interactive* – http://hotmix.ce.washington.edu/wsdot_web – "... Although buses are sometimes ignored in truck counts, they can significantly contribute to overall pavement loading - especially in urban areas. Many times, school buses provide the only major loading for residential pavements. Furthermore, buses often inflict more pavement damage than much heavier trucks due to their axle configurations and wheel loads." See Attachment 1, herein.

During the City of Spokane's residential bond resurfacing initiative in the mid-1980s, there were many local access streets that had been in service for 50 years or more, whose major distress was the result of environmental conditions – primarily pavement oxidation resulting from exposure to the ultraviolet rays contained in normal sunlight. These areas responded well to minimal treatment. However, it was not uncommon to find a local access street that had undergone total structural failure intermingled with other streets that were in reasonably good shape. Invariably, these areas of structural failure were on bus routes. In fact, in at least one case, only one-half of a street had failed structurally and as might be expected, that side of the roadway was located on the return leg of a bus route.

Other Considerations. The above information notwithstanding, the FHWA Vehicle Classifications would classify a “typical” bus as a (FHWA) Class 4 vehicle with 0.57 ESALs per vehicle. In their Pavement Management System, the Washington State Department of Transportation (WSDOT) assigns 0.4 ESALs to their single unit category, which includes the FHWA Class 4 vehicle. However, based on other data WSDOT assigns 1.6 ESALs to non-interstate urban buses.

Example. Assume a new local access street has just been put in service. The analysis period was 20 years, and the anticipated loading was based on a current service level consisting of the occasional delivery truck (assume 10 per day; assume 0.5 ESAL per truck), local single passenger vehicles (assume 200 per day; assume 0.0004 ESAL per vehicle), and 2 garbage trucks per week (assume 3 ESALs per truck). For the ease of calculation, assume that no growth was anticipated.

Over the course of the 20 year analysis period, then the total ESAL count assumed for the design of the pavement structure was about 20*(365*(10*0.5+200*.0004)+52*2*3.0), or only about 43,000 ESALs. This is about 6 ESALs per day.

Now, assume that after, say 2 years the roadway became designated a bus route, with an average of 30 buses per day. Assuming that each bus equated to about 1.25 ESALs, the same 43,000 ESALs would be reached in only about 2+((43,000-(365*2*6))/(6+30*1.25))/365 = 4.4 years!

To be sure, the minimum pavement thickness specified by many jurisdictions can accommodate considerably more than 43,000 ESALs during a 20-year analysis period, assuming average structural and environmental conditions. Typically, then, the minimum pavement thicknesses can be expected to last longer than the normal 20-year analysis period, assuming the normally smaller traffic of local access roads. However, it is readily apparent that the addition of numerous heavy axle loads will significantly reduce the service life of a (local access) roadway.

Conclusions and limitations. It is important that the above information be considered within the paper’s intended scope. The fact is, the numbers are based primarily on *empirical data* from the AASHO Road Test of the late 1950’s, together with subsequent industry observations and analytical work. **The numbers must not be considered “exact”**. Rather, they must be viewed as being generally representative of the observed performance of numerous past and current pavement systems, and as having been demonstrated suitably appropriate for predicting future pavement performance.

Consideration of the above Vehicle Load Factors and accompanying discussion reveals a number of interesting, even startling relationships concerning the damage – reduction in serviceability index – imparted to the street system by various vehicles:

- The average EMPTY bus in the above data is about equivalent to nearly 3,000 passenger cars in terms of "damage" imparted to the pavement infrastructure.
- Some *empty* buses are about equivalent to a *loaded* 7 cubic yard concrete truck.
- Full buses exceed the "damaging" effect of a loaded 10 cubic yard concrete truck.
- During the course of an **average day**, the pavement "damage" along a typical transit route *that is attributable to the bus traffic alone* is roughly equivalent to that imparted by 60 thousand passenger cars (assuming 30 buses per day) – nearly 200 thousand ESALs during a typical 20-year analysis period **– and that's assuming the lightest, EMPTY bus contained in the above table.**
- Although some garbage and fire trucks may have a larger ESAL total (VLF) than some buses, garbage and fire trucks typically impart nowhere near the "damage" imparted by buses, *for those (local access) streets on a transit route*. This is due to the reduced number of garbage and fire truck trips as compared to the bus trips.
- On probably all residential bus routes and many – if not most – arterial bus routes, bus traffic is arguably the single defining loading for which the pavement section should be designed.

<u>Recommendations.</u> Clearly, heavy traffic – most notably bus traffic – is a major factor in the life of a street, particularly a local access street. Consequently, attention must be paid to how these heavy loads will circulate within and through neighborhoods.

While it is possible to anticipate heavy loads and design pavement sections accordingly, it does not make economic sense to do so if such loads do not subsequently materialize – there is simply too much demand for current money. Perhaps equally important, any consideration to apply heavy loads to a street not appropriately designed therefor – e.g. changing a garbage truck route, or even more seriously changing a bus route – should be made with full knowledge of the ramifications.

Accordingly, it would not be inappropriate to require any agency, jurisdiction or entity that is considering actions that would impart significant heavy loading to a pavement structure not intended for that use – or, for that matter to any pavement structure – to pay into a fund to offset the cost associated with the inevitable accelerated pavement deterioration and related early required maintenance and repair. Perhaps the monetary "damages" could/should be related to the increase in ESALs imparted by the action of the responsible agency or entity. This notion is very similar to the concept of developer impact fees relating to residential or commercial/industrial development, and their effects on the transportation network.

It is especially appropriate that STA take into account these pavement service life factors and associated real – not "soft" – cost implications when considering route changes, particularly if the changes affect local access streets. It is important for the citizens of Spokane to understand the full implications of any decisions that have major effects on their – not "the City's" – infrastructure. If it is subsequently determined that "hard" payment is not appropriate, then the related costs should be accounted for as social costs or in some other manner so that they appear in the balance sheet, and do not become hidden and thus forgotten.

Attachment 1

From Washington State Department of Transportation, *Pavement Guide Interactive* Module 4, Section 3.6.1, Additional Information on Trucks and Buses link

Notes on Buses

Although buses are sometimes ignored in truck counts, they can significantly contribute to overall pavement loading - especially in urban areas. Many times, school buses provide the only major loading for residential pavements. Furthermore, buses often inflict more pavement damage than much heavier trucks due to their axle configurations and wheel loads. As shown in Table 3, a heavily loaded, dual powered bus (both diesel and electric power systems) can impart over 6 ESALs per bus. Table 3 tabulates various bus LEFs for King County (WA) Metro.

Table 3: Representative Bus ESALs (Metro, 1987; DeBoldt, 1993)

Bus	ESALs/Bus	Bus	ESALs/Bus
• AM General Diesel		• MAN 60'	
• Empty	1.14	• Empty	0.84
• 50% Full	1.67	• 50% Full	1.42
• 100% Full	2.34	• 100% Full	2.20
• 130% Full	2.85	• 130% Full	2.87
• AM General Trolley		• Flexible Diesel	
• Empty	0.80	• Empty	0.57
• 50% Full	1.22	• 50% Full	0.94
• 100% Full	1.78	• 100% Full	1.50
• 130% Full	2.19	• 130% Full	1.92
• Flyer		• GM Diesel	
• Empty	0.96	• Empty	0.58
• 50% Full	1.45	• 50% Full	0.95
• 100% Full	2.11	• 100% Full	1.46
• 130% Full	2.61	• 130% Full	1.84
• Flyer Diesel		• Breda 60'	
• Empty	0.85	• Empty	2.53
• 50% Full	1.21	• 50% Full	3.63
• 100% Full	1.67	• 100% Full	5.11
• 130% Full	2.02	• 130% Full	6.17
• MAN 40'			
• Empty	1.27		
• 50% Full	1.80		
• 100% Full	2.67		
• 130% Full	3.29		

Note: 130% Full is all seats filled with standing passengers

If no other information is known about a bus route other than the volume of buses, use an ESAL/bus corresponding to 50 percent full. This results in an average ESAL/bus $\cong$ 1.60.

Table 4 shows the detailed King County Metro numbers used to calculate the values in Table 3.

Table 4: Seattle Metro Bus Data

Bus Type	Total Empty Weight (lb)	Tire Size[3,4]	Seating Capacity	Weight (pounds) and ESAL per Axle											
				Empty			50% Full Pax			100% Full Pax			130% Full Pax		
				1st Axle	2nd Axle	3rd Axle	1st Axle	2nd Axle	3rd Axle	1st Axle	2nd Axle	3rd Axle	1st Axle	2nd Axle	3rd Axle
AM General Diesel[1]	26,600	12.5 x 22.5	45	8,200	18,400	—	9,925	20,200	—	11,350	22,000	—	12,295	23,088	—
				0.04	1.10	—	0.09	1.58	—	0.16	2.18	—	0.21	2.64	—
AM General Trolley[1]	24,740	12.5 x 22.5	45	7,980	16,760	—	9,555	18,560	—	11,130	20,360	—	12,075	21,440	—
				0.03	0.77	—	0.08	1.14	—	0.15	1.63	—	0.20	1.99	—
Flyer[1] 40'	26,300	12.5 x 22.5	47	8,850	17,450	—	10,500	19,325	—	12,150	21,200	—	13,140	22,325	—
				0.06	0.90	—	0.11	1.34	—	0.20	1.91	—	0.29	2.32	—
MAN[1] 60' Articulated	37,300	12 x 20	70	12,900	15,100	9,280	14,716	17,226	10,587	16,281	19,226	12,272	17,295	20,464	13,675
				0.27	0.50	0.07	0.45	0.85	0.12	0.68	1.31	0.21	0.87	1.67	0.33
Flxible Diesel[1]	22,770	12.5 x 22.5	51	7,410	15,360	—	9,210	17,310	—	11,010	19,410	—	12,090	20,625	—
				0.03	0.54	—	0.07	0.87	—	0.14	1.36	—	0.20	1.72	—
GM Diesel[1] 35'	21,640	12.5 x 22.5	48	6,020	15,620	—	7,670	17,570	—	9,320	19,520	—	10,310	20,690	—
				0.01	0.57	—	0.03	0.92	—	0.07	1.39	—	0.10	1.74	—
Flyer Diesel[1] 35[1]	24,470	12.5 x 22.5	39	7,420	17,050	—	8,770	18,625	—	10,120	20,200	—	10,930	21,145	—
				0.03	0.82	—	0.05	1.16	—	0.09	1.58	—	0.13	1.89	—
MAN[2] 40'	28,240	12.5 x 22.5	45	10,000	18,240	—	11,215	20,428	—	12,431	22,617	—	13,160	23,930	—
				0.09	1.18	—	0.15	1.65	—	0.23	2.44	—	0.29	3.00	—
Breda[2] 60' Articulated	49,330	12.75 x 22.5 (steer)	67	13,257	15,546	20,527	14,207	18,043	22,117	15,156	20,540	23,707	15,726	22,038	24,661
		12.5 x 22.5		0.30	0.56	1.67	0.39	1.01	2.23	0.51	1.69	2.91	0.59	2.20	3.38