Final Report

Analysis of the Infrastructure Impacts of Heavy-duty Vehicle 6x2 Axle Technologies on Canadian Provincial and Territorial Roadways for Transport Canada (TC)

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Table of Contents

Lists of Figures

Lists of Tables

1.0 Introduction

Use of a 6x2-axle configuration on highway tractors, as opposed to the more traditional 6x4-axle configuration, may lead to fuel savings and reductions in GHG emissions (NACFE, 2014). The 6x2-axle design employs a single drive axle instead of the two drive axles employed by a conventional 6x4 system, thus eliminating the internal mechanical losses and mass associated with components such as the inter-axle drive shaft and differential.

With only one drive axle, however, tractors may suffer from reduced traction in certain conditions. To mitigate this problem, manufacturers offer systems capable of transferring load between the drive axle and the non-drive axle. This shift in loading may result in load levels beyond the current allowable limits in some provinces and territories.

Truck and traffic loading, environmental conditions, soil, and maintenance are key variables that affect pavement performance. With variable load systems that can transgress the allowable limits for loading, the potential for road surface damage opens up. Seasonal shifts can also amplify higher levels of road surface damage during the spring thaw. The North American Council for Freight Efficiency (NACFE) (2014) & The National Research Council Canada (2016) have examined loading configuration, fuel consumption, and traction in previous studies.

1.1 Project Scope and Objectives

The primary objective of this work is to analyze and report on the potential impact of 6x2 load-shifting technologies on Canadian road infrastructure. Test data will be acquired from National Research Council research team (Chuang, 2018) to perform damage analysis. Results should show the relationship between pavement degradation and 6x2 technology under a range of scenarios.

1.2 Research Process

All of the tasks that were identified in the project kick-off meeting have been completed.

Table 1 Progress-to-Date on Project Proposed Tasks

Task	Status
Task 1: Project Kick-off Meeting	Complete
Task 2: Data Collection	Complete
Task 3: Methodology	Complete
Task 4: Survey	Complete
Task 5: Conduct Damage Analysis	Complete
Task 6: Perform preliminary analysis	Complete
Task 7: Draft Final Report	Complete
Task 8: Presentation	Complete

1.3 Research Methodology

Figure 1 presents the methodology that was followed in this project.

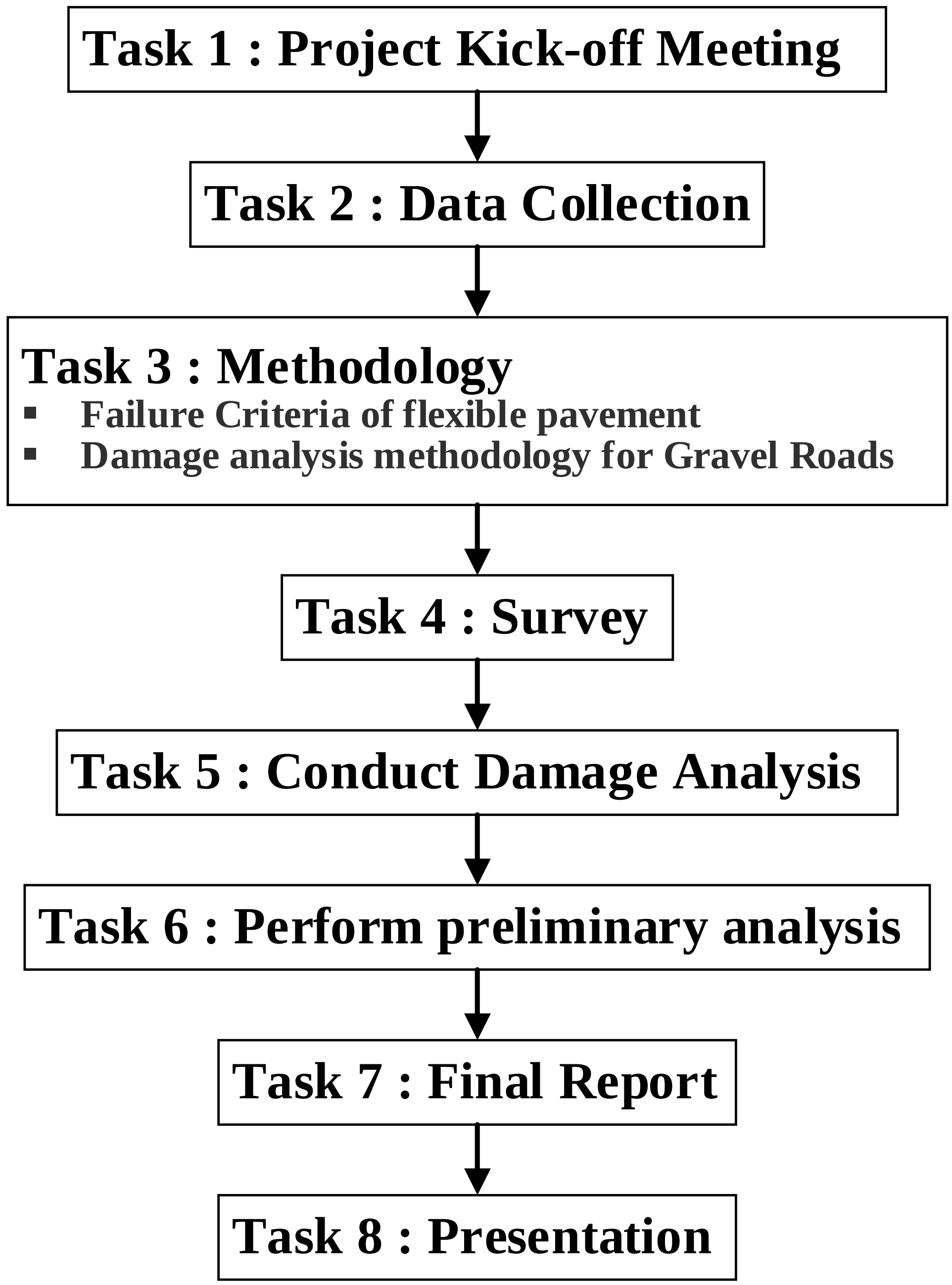

Figure 1 Research Methodology

2.0 Data Collection

In Winter 2018, the National Research Council (NRC) conducted a vehicle driving test on 6x2 and 6x4 vehicles. Wheel force transducers were installed on the tandem axle in the tractor to obtain dynamic axle data during the test. Five different tractor axle loads were tested which are shown in Table 2. The test data were presented in Appendix C. The test vehicles included three manufacturers, which are Kenworth, Freightliner, and Volvo. The testing consisted of acceleration from stop on an ice patch, transitioning to dry pavement and continuing up to 80 km/h on a 6.5 km track, then returning to a stop on the ice patch (Chuang, 2018). It should be noted that the Kenworth 6x2 capped the drive axle load at 7,400 kg in static condition, and the target of 10,000kg/axle on the drive axle set could not be reached.

It is important to note that according to the Heavy Truck Weight and Dimension Limits for Interprovincial Operations in Canada prepared by the Task Force on Vehicle Weights and Dimensions Policy in 2014, the weight limit for tandem axle sets on tractor semitrailers on the designated highway system is 17,000 kg, or “85% load condition” in this report. Jurisdictions retain authority to allow more liberal weights for trucking operations within their jurisdiction. For example, an 18,000 kg weight limit, or “90% load condition”, would be representative of weight limits in Eastern Canada.

Table 2 Tested Tractor Axle Loads (Target)

100%	85%	70%	50%	0%
10,000 kg	8,500 kg	7,000 kg	5,000 kg	Empty trailer

3.0 Methodology

3.1 Failure Criteria for flexible pavement

In flexible pavement structures, fatigue cracking and permanent deformation, namely rutting are the two primary failure criteria for pavement performance. In order to have an understanding of how many loadings the pavement structure can bear before these two failures occur, the allowable number of load repetition before fatigue cracking and rutting were calculated via the use of Weslea software. The input parameters required in Weslea are pavement structure, layer properties, tire pressure, and loads. According to the typical Ontario pavement design report from Applied Research Associates (2015), the typical thickness of the four classes are listed in Table 3. The typical flexible pavement thickness in Ontario is usually a three-layer structure, which consists of a hot-mix asphalt surface layer over a granular A base layer, and a thick granular B subbase layer on top of the subgrade soil. The Elastic Modulus and the Poisson Ratio of the three layers at different seasons are also assumed based on engineering experience and demonstrated in Table 4.

The tire pressure is assumed to be 862 kPa (125 psi), while the axle loads are assumed to be an 80 KN (18-kips) single axle load.

Table 3 Layer thickness of different road level

Layer	Thickness (cm)			
	Highway	Major Arterial	Minor Arterial	Collector
Surface	21	18	14	12
Base	20	15	15	15
Subbase	60	50	30	30
Subgrade	-	-	-	-

Table 4 Material Properties at different seasons

Season	Elastic Modulus (MPa)				Poisson's Ratio
	Surface Layer	Base	Subbase	Subgrade	
Winter	13,500	250	200	150	0.35
Spring Thaw	2,800	100	100	30	0.35
Summer	1,378	150	130	80	0.35
Fall	2,800	150	130	80	0.45

In order to evaluate the exact pavement impact of the vehicles, equivalent single axle load (ESAL) is introduced to assess the level of impact from the traffic loadings. To calculate ESAL, it is necessary to understand the load equivalency factor (truck factor) of the vehicles. The truck factor can be calculated using the following equation:

$$\text{Approximate load equivalency factor} \cong \left(\frac{axle\ load}{18{,}000lb\ (80kN)\ one\ axle\ load}\right)^4 \qquad (1)$$

Traffic loading is the most important factor in pavement design. The thickness of the pavement is calculated by the number of repetitions of a standard vehicle or axle load, which is an 80KN (18-kip) single axle load. Any axle load that is not 80KN (18-kip) or consists of tandem or tridem axle must be converted into an 80KN (18-kip) single axle load. After the axle loads are transformed into 18-kip single axle load, the summation of all loads during the design period is known as equivalent single axle load (ESAL) (Huang, 1993). The equation for calculating ESAL is:

$$\text{ESAL} = (ADT)_0(T)(T_f)(G)(D)(L)(365)(Y) \qquad (2)$$

where:

ESAL =Equivalent Single Axle Load
$(ADT)_0$ =Average daily traffic at the start of the design period
T =Percentage of trucks in ADT
T_f =Number of 18-kip(80-kN) single axle load applications per truck
G =Traffic Growth factor, (%)
D =Directional distribution factor, (%)
L =Lane distribution factor, (%)
Y =Design period in years

To calculate the ESALs of 6x2 and 6x4 truck, several assumptions are made in this section. Firstly, four road levels had been classified and used in this research. The four road levels are Highway, Major Arterial, Minor Arterial, and Collector as classified in the TAC guide (2013). Secondly, the average daily truck traffic is taken from the Ontario pavement design report from Applied Research Associates (2015). Thirdly, the directional distribution factor is set to be 0.5 for both directions, while the lane distribution factor is 0.7 for Highway, 0.9 for Arterial road and 1 for Collector and Gravel road. The design period is the number of years for the design.

Once the allowable number of load repetitions and ESAL were calculated, the damage ratio could be obtained by dividing the allowable number of load repetitions by the ESAL. If the damage ratio is over or equal to one, the failure will occur.

3.2 Damage analysis methodology for Gravel Roads

In the American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures (AASHTO 1993), Equivalent Single Axle Load (ESAL) is considered vital to gravel road thickness design. The design method is based on the trial-and-error approach. It assumed the thickness and calculated the expected damage due to serviceability and rutting criteria. In this analysis, the serviceability and rutting criteria generated by the two vehicles will be presented. The detailed procedures are listed below:

1. Select trial base thickness.

   Six trial thickness are assumed in this analysis, which are 17.78, 20.32, 22.86, 25.4, 27.94, 30.48, 33.02, and 35.56 cm (7, 8, 9, 10, 11, 12, 13, and 14 inch).

2. Select an allowable serviceability loss (ΔPSI), and allowable rutting depth (RD)

   The allowable serviceability loss (ΔPSI) is assumed to be 2.0 for low volume road, and the allowable rutting depth (RD) is set to 5 cm (2 inches).

3. Select seasonal resilient modulus for roadbed (M_R) and elastic modulus of the aggregate base

material (E_{BS})

The seasonal resilient modulus for roadbed (M_R) and elastic modulus of the aggregate base material (E_{BS}) is assumed and listed in Table 5.

4. Determine projected 80KN (18-kip) ESAL traffic

   Seasonal 80KN (18-kip) ESAL traffic is calculated and demonstrated in Table 6.

5. Determine allowable 80KN (18-kip) ESAL traffic for serviceability criteria

   The allowable 80KN (18-kip) ESAL traffic for serviceability criteria can be determined by using the serviceability-based nomograph. The results are shown in Table 5 as an example.

6. Determine allowable 80KN (18-kip) ESAL traffic for rutting criteria

   The allowable 80KN (18-kip) ESAL traffic for rutting criteria can be estimated by using the rutting-based nomograph. The results are presented in Table 5 as an example.

7. Determine seasonal damage (serviceability and rutting criteria)

   The seasonal damage can be calculated by dividing the projected 80KN (18-kip) ESAL traffic by allowable traffic in that season.

After the pavement damage is determined, compute a chart with thickness and pavement damage. The layer thickness will be determined by interpolating in this graph for total damage equal to 1.0.

Table 5 Example Chart for computing Total Pavement Damage (Trial base Thickness = 25.4 cm)

Season	**Roadbed Resilient Modulus MR (psi)**	**Base Elastic Modulus MR (psi)**	**Projected 80KN (18-kip) ESAL Traffic, W18**	**Allowable 80KN (18-kip) ESAL Traffic PSI**	**Seasonal Damage, W18/(W18) PSI**	**Allowable 80KN (18-kip) ESAL Traffic, (W18)**	**Seasonal Damage W18/ (W18) RUT**
Winter	20,000	25,000	7,767	500,000	0.016	65,000	0.119
Spring/thaw	2,000	25,000	4,660	7,250	0.643	6,000	0.777
Spring Fall	6,000	25,000	12,427.95	25,000	0.497	20,000	0.621
Summer	10,000	25,000	12,427.95	65,000	0.191	37,000	0.336
		Total	**37,284**		**1.347**		**1.854**

Table 6 Example of ESAL calculation for gravel road design

Industry	Configuration	AADTT	Day	Growth (0%)	DSF	LD	TF	years	ESAL
FL	**6x2 100% max tf**	50	365	1	0.5	0.7	5.816	1	37,150
	6x4 100% max tf	50	365	1	0.5	0.7	5.529	1	35,316
	6x2 100% avg tf	50	365	1	0.5	0.7	4.935	1	31,522
	6x4 100% avg tf	50	365	1	0.5	0.7	4.842	1	30,928
	6x2 100% min tf	50	365	1	0.5	0.7	4.390	1	28,041
	6x4 100% min tf	50	365	1	0.5	0.7	4.271	1	27,281

3.3 Survey

An online survey was also used in this study to obtain information regarding the pavement structure and system within the jurisdictions in Canada. In order to choose respondents for this online survey, the expert sampling method was used. The list and email addresses of professionals working with either the city, region or ministry in a capacity that involved pavement related issues and were part of the Transportation Association of Canada was obtained. The survey was administered via email to each of the professionals that met the above criteria.

The questions asked in the survey required the respondents to indicate their province and positions; this was to enable further the assessment of their ability to provide answers to the subsequent questions and to determine which province each response was for. Furthermore, details about the type of road network, pavement structure and the main type of pavements and distresses encountered in their specific jurisdictions was requested. The expectation regarding the distresses that might occur due to the use of the 6 x 2 vehicle within each province was also sought. The questions were multiple choice, selecting options that applied and some open-ended questions. A sample of the survey is provided in Appendix D.

4.0 Results and discussion

4.1 Survey result

The results obtained from the online survey administered to various professionals across provinces in Canada are presented in this section. Eighteen surveys were sent out with a response rate of 56%. Responses were obtained from most provinces and territories except British Columbia, the Northwest Territory, Nova Scotia, Prince Edward Island and Nunavut. A summary of the results is presented in Table 7 and 8. Respondents worked with either the city, the region, the ministry in infrastructure, construction and specifically pavement related areas and were well suited to respond to the questions asked as a selective sampling method was employed to determine respondents.

Generally, most regions have a higher percentage of flexible pavement compared to other pavement types; hence, it is expected that the 6 x 2 trucks will mostly use flexible pavements. In New Brunswick and Yukon, chip seal pavements are predominant, and this should also be noted when designing for 6 x 2 vehicles in these jurisdictions and other colder regions. The main challenges currently faced on most roads in the jurisdictions include fatigue cracking, transverse and longitudinal cracking, permanent deformation/rutting, depressions and ravelling. Reasons for these distresses range from wear and tear due to high traffic loading, especially in the winter, pavement structure already approaching the end of life, extremely low temperature, material quality and insufficient layer thickness.

It is anticipated that the distresses that could occur due to the introduction of the 6 x 2 vehicles would include fatigue cracking, permanent deformation/rutting, longitudinal cracking and depressions. It should be noted that respondents from Alberta indicated that if the 6x2 vehicle has a lift axle, Alberta Transportation will not allow it.

It was also observed that pavement thicknesses for most regions, according to the ranges provided for flexible pavement were quite similar. The expected road level that 6 x 2 vehicle is expected to travel varies from province to province with some provinces indicating use on only Urban roadways while others signify both Rural and Urban.

Table 7 Survey results of each jurisdiction - 1

Jurisdiction	Main pavement type	Road level for 6 x 2	Pavement structure	Proportion of pavement types	Distresses that occur an major pavements	Most significant distress and why	Expected distresses caused by 6 x 2
Newfoundland and Labrador	Flexible	Rural Highway, Rural Arterial road, Rural Collector	50mm to 110mm of Asphaltic Materials 250mm to 450mm of Granulars		Fatigue cracking, Permanent deformation / Rutting, Depression, Longitudinal cracking, Rutting caused by pavement wear. No seasonal/spring load restrictions.	Pavement wear during the winter caused by studded tires on high speed, high traffic environments. Rural Collections tend to face more structural issues.	Fatigue cracking, Depression, Longitudinal cracking
Quebec	Flexible, Rigid , Composite (rigid with an asphalt overlay)	Urban Highway, Rural Highway, Urban Arterial road, Urban Collector	Highways > 200 mm thickness, Arterial road: concrete 200mm, asphalt overlay: 75mm Urban collector: asphalt- 300mm In both cases,with a gravel foundation of 300 mm	**Highways**: 83.3% Flexible, 16.7% Rigid Urban: 60% Flexible, 40% Composite	Fatigue cracking, Permanent deformation / Rutting, Longitudinal cracking, Transversal cracking, potholes	Fatigue, longitudinal and transversal cracking, rutting in the wheel paths Most road network built in the 60s therefore reached end of useful life.	Fatigue cracking, Permanent deformation / Rutting, potholes
Manitoba	Flexible, Rigid, Gravel road, Chip seal		Rigid - 250mm concrete, 150-300mm base flexible - 100-200mm bituminous, 300-800mm base chip seal - double chip seal over 75-300mm base gravel - 75-150mm base		Fatigue cracking, Permanent deformation / Rutting, Raveling, Longitudinal cracking	Thermal cracking due to extremely low temperatures	Permanent deformation / Rutting, , Corrugation and Shoving
Alberta	Flexible	Urban Highway, Urban Expressway, Urban Arterial road, Urban Collector	There is no truly "typical" section. However, approximately 250 mm Asphalt layer over 300 Granular Base/Subbase would be considered normal.	90% flexible, 10% others	Fatigue cracking, Permanent deformation / Rutting, Raveling, Longitudinal cracking, Transverse cracking / Low temperature cracking and segregation	Low temperature cracking which always require signiicant maintenance. Generally pavement structural design life is 20 years, therefore requires rehabilitation for strength. Granular layers are not overly thick and no frost protection.	Fatigue cracking, Permanent deformation / Rutting, , Longitudinal cracking

Table 8 Survey results of each jurisdiction - 2

Jurisdiction	Main pavement type	Road level for 6 x 2	Pavement structure	Proportion of pavement types	Distresses that occur an major pavements	Most significant distress and why	Expected distresses caused by 6 x 2
Saskatchewan	Flexible	Urban Highway, Rural Highway	100 to 200mm asphalt surface layer		Fatigue cracking, Permanent deformation / Rutting, Thermal Cracking	Cracking	Permanent deformation / Rutting, Corrugation and Shoving, Fatigue cracking over a long period of time
New Brunswick	Flexible , Rigid , Gravel road, Chip seal	Urban Highway, Urban Expressway, Urban Arterial road, Urban Collector, Urban Local road, Rural Highway, Rural Arterial road, Rural Collector, Rural Local	Typical AC layer (base+seal) is 140mm, but there is wide variability throughout the system	34% Flexible, 0.04% Rigid, 28% Gravel , 38% Chip Seal	Fatigue cracking, Permanent deformation / Rutting, Raveling, Bleeding, Corrugation and Shoving, Depression, Longitudinal cracking	Fatigue cracking and rutting are most common	Fatigue cracking, Permanent deformation / Rutting, Corrugation and Shoving, Depression, Longitudinal cracking
Yukon	Flexible pavement, Gravel road, Chip seal	Urban Highway, Urban Expressway, Urban Arterial road, Urban Collector, Urban Local road, Rural Highway, Rural Arterial road, Rural Collector, Rural Local, Mine Roads	150 - 250mm Base Coarse, 300 - 600mmSubbase 50 - 80mm asphalt where it exists	Mostly Chip seal and Gravel Roads, very few kms of the asphalt Roads	Fatigue cracking, Permanent deformation / Rutting, Raveling, Depression, Longitudinal cracking	Longitudinal and fatigue cracking in the asphalt pavement, Depression and rutting in the chip seal, Depression in the permafrost affected areas	Fatigue cracking, Permanent deformation / Rutting, Raveling, Depression, Longitudinal cracking
Ontario	Flexible	Urban Highway, Urban Expressway, Urban Arterial road, Urban Collector, Rural Highway, Rural Arterial road, Rural Collector	100 - 150 mm HMA 150 - 200 mm Granular Base 400 - 600 mm Granular Subbase		Fatigue cracking, Longitudinal cracking, Transverse Cracking	Transverse Cracking/Low Temperature Cracking, multiple reasons including asphalt binder quality.	Fatigue cracking

4.2 Truck Factor of the two configuration truck

The truck factors of each vehicle with different loading condition are presented in this section. Three different types of manufacturer's vehicles were involved in this test, which is V, K and F. 6x4 and 6x2 axle vehicle is classified as Model A, and B, respectively. The test data that was used to convert into truck factor was obtained from the Dynamic Axle Load test which performed by NRC in 2018 (Chuang, 2018). Figure 2 to 4 shows the truck factor of the three manufacturers' vehicle at different loading condition.

Figure 2 presents the truck factor of the V Manufacturer's vehicle. It is clear that 6x2 configuration has higher truck factor than the 6x4 configuration at 70%, 50%, and 0% load condition. The truck factor of the two configurations has a similar average value at 85% load condition. However, the 6x2 truck has more and higher values of an outlier (black dots) compared to the 6x4 truck. This is due to the load transfer system installed on the 6x2 vehicle. At slippery or low-speed conditions, the shifted load would significantly increase the axle load on one of the axles and truck factor value. At 100% load condition, the 6x4 configuration truck has a wider interquartile range compared to 6x2. This could be due to the failure of the sensor on the left wheel of the 6x4 truck which is mentioned in the NRC report (Chuang, 2018), which resulted in lower average and minimum truck factors.

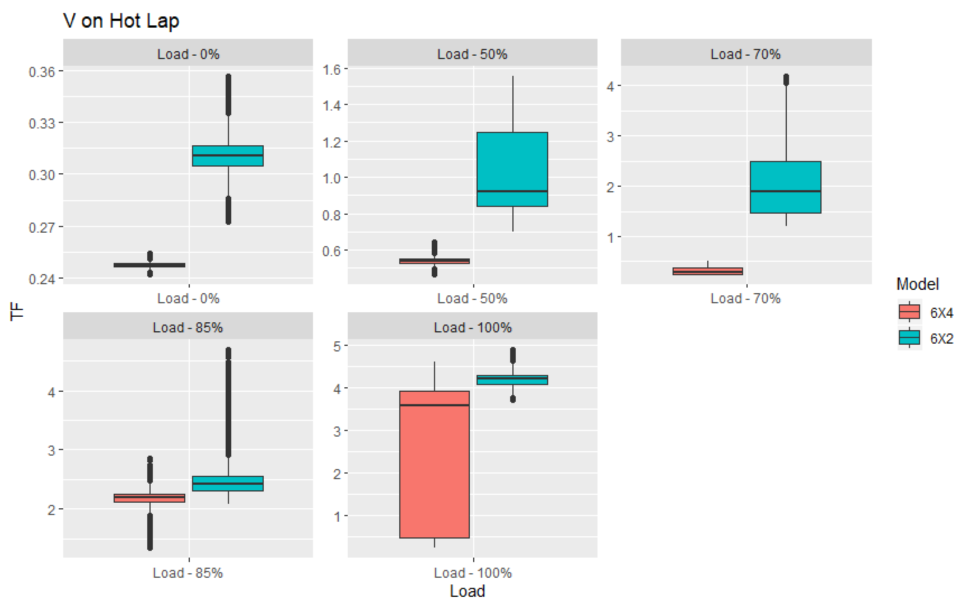

Figure 2 Truck factor of V Manufacturer's vehicle

Figure 3 demonstrates the truck factor of K Manufacturer's vehicle. It is clear that the average truck factor of 6x2 configuration is similar to 6x4 configuration, but the outlier of the 6x2 truck is significantly higher than 6x4 truck. The difference becomes even more significant at 85% load condition.

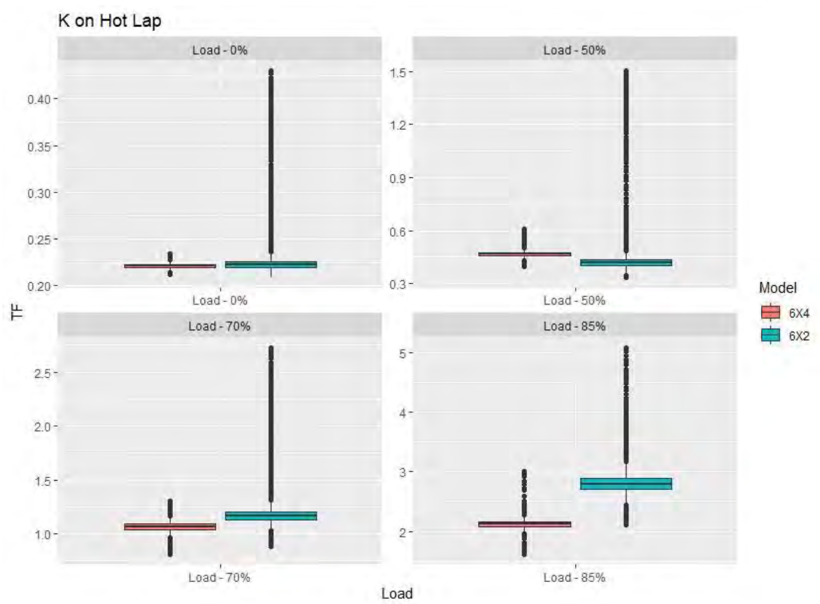

Figure 3 Truck factor of K Manufacturer's vehicle

Figure 4 demonstrates the truck factor of F Manufacturer's vehicle. At load condition below 85%, it has the same trend as K manufacturer vehicle with similar average truck factor but higher outliers. However, the 6x2 and 6x4 vehicle perform in the same way at 85% load condition. Though 6x2 truck still has higher outlier values.

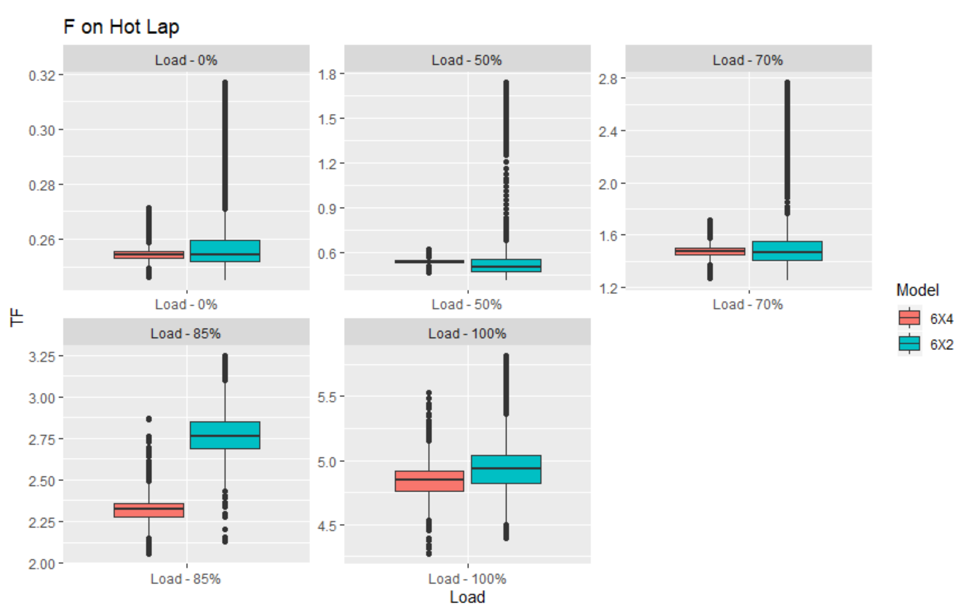

Figure 4 Truck factor of F Manufacturer's vehicle

4.2.1 Empirical Cumulative Distribution of Truck Factor

Empirical cumulative distribution of all the truck factors has been presented in Figure 5 to 7. The truck factor distribution for the three manufacturer's 6x4 and 6x2 truck varies based on their truckload shifting mechanism. Table 9 listed the truck factor of Freightliner vehicle.

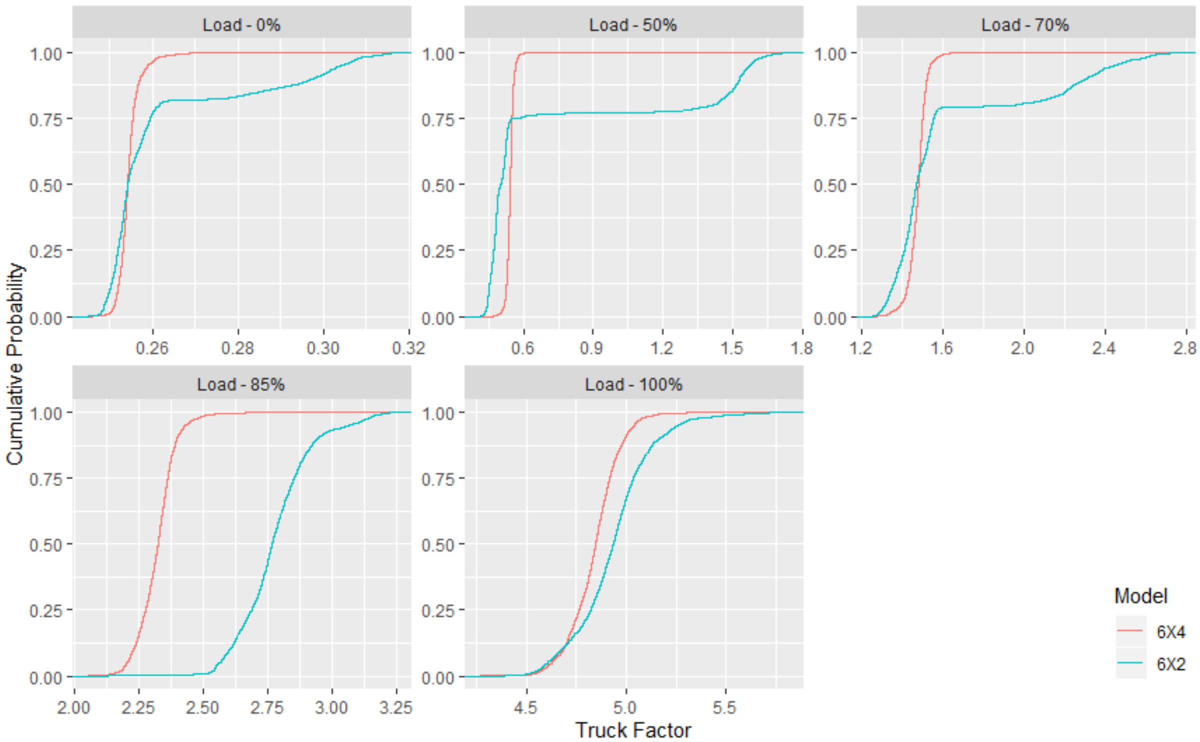

Figure 5 Empirical Cumulative Distribution of the Freightliner truck factor

The truck factors of Freightliner's 6x4 and 6x2 trucks show similar distribution at 100% load condition, with 6x4 truck ranging from 4.5 to 5.0 and 6x2 truck from 4.5 to 5.3. However, the 6x2 truck has a broader distribution than 6x4 truck at lower loadings (0%, 50%, 70%, and 85%), this is because both magnitude and duration of load shift was higher at the lower loads compared to at 100% load, which could lead to significant truck factor differences compared to the 6x4 truck.

Table 9 Average, Maximum, and minimum truck factor of Freightliner vehicle

Vehicle	Model	Load(%)	TF.avg	TF.max	TF.min
F	A	0	0.254	0.271	0.246
F	A	50	0.543	0.625	0.470
F	A	70	1.472	1.712	1.270
F	A	85	2.320	2.873	2.053
F	A	100	4.842	5.529	4.271
F	B	0	0.262	0.317	0.245
F	B	50	0.724	1.740	0.417
F	B	70	1.620	2.770	1.253
F	B	85	2.776	3.249	2.129
F	B	100	4.935	5.816	4.390

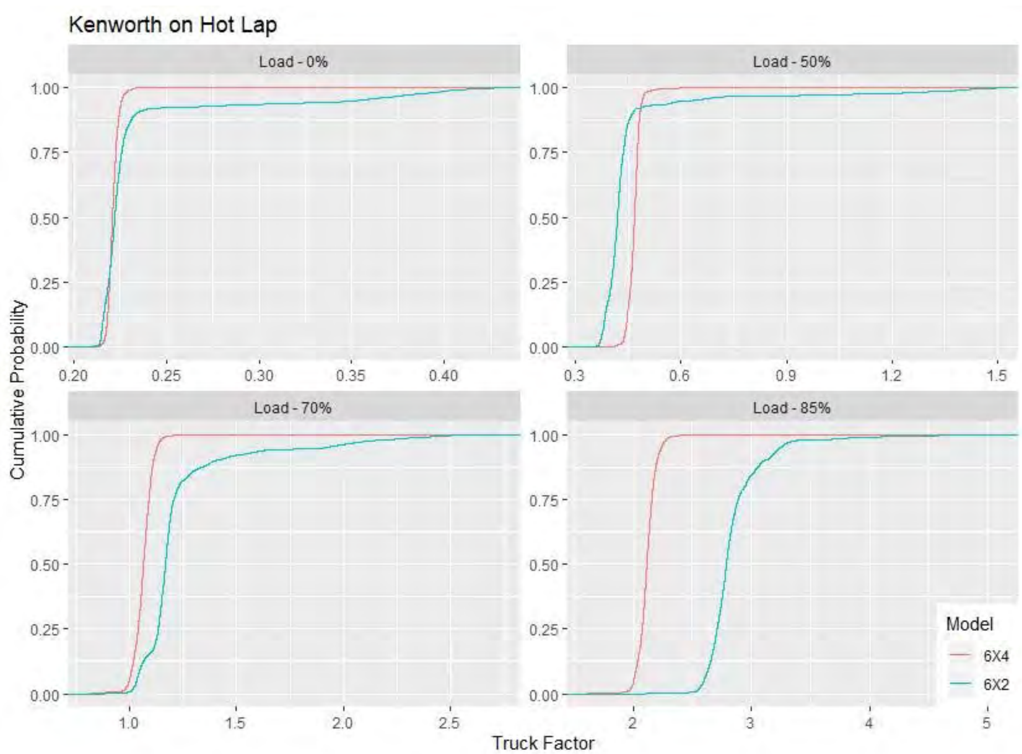

Figure 6 Empirical Cumulative Distribution of the Kenworth truck factor

The truck factor distribution of 6x2 and 6x4 for Kenworth at 0%, 50%, and 70% load has a similar trend. However, at 85% load levels, it can be seen that 6x2 truck has a broader distribution and higher maximum truck factor than the 6x4 truck, which is also observed in Freightliner 6x2 truck at 85% load condition. Table 10 lists the truck factor of the Kenworth vehicle.

Table 10 Average, Maximum, and minimum truck factor of Kenworth vehicle

Vehicle	Model	Load(%)	TF.avg	TF.max	TF.min
K	A	0	0.221	0.234	0.212
K	A	50	0.466	0.612	0.396
K	A	70	1.065	1.306	0.813
K	A	85	2.12	3.012	1.618
K	B	0	0.232	0.43	0.208
K	B	50	0.45	1.503	0.334
K	B	70	1.231	2.729	0.882
K	B	85	2.847	5.088	2.105

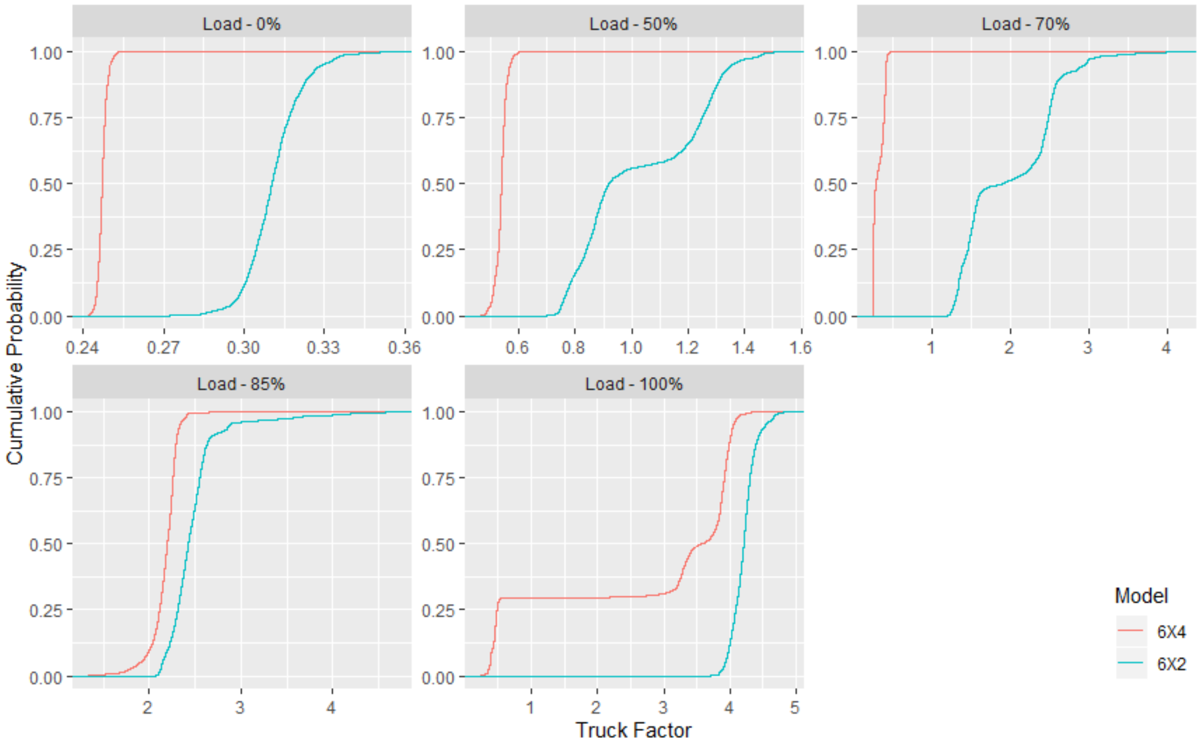

Figure 7 Empirical Cumulative Distribution of the Volvo truck factor

The Cumulative Distribution of the Volvo truck factor for the two vehicles has a similar trend at 85% load. However, unlike the Freightliner and Kenworth vehicles, which have a similar average truck factor at lower load condition. The Volvo 6x2 truck at 0%, 50%, and 70% has a higher initial truck factor than the 6x4 vehicle. The trend of 6x4 at 100% load react differently than others could be due to the sensor failure on the left wheel. Table 11 listed the truck factor of Volvo vehicle.

Table 11 Average, Maximum, and minimum truck factor of Volvo vehicle

Vehicle	Model	Load(%)	TF.avg	TF.max	TF.min
V	A	0	0.247	0.254	0.242
V	A	50	0.537	0.646	0.465
V	A	70	0.317	0.508	0.249
V	A	85	2.171	2.853	1.338
V	A	100	2.754	4.604	0.241
V	B	0	0.311	0.357	0.272
V	B	50	1.028	1.558	0.698
V	B	70	1.991	4.190	1.191
V	B	85	2.476	4.697	2.070
V	B	100	4.209	4.896	3.713

4.3 Result of Damage Ratio for Flexible pavement

The results for the damage analysis already described in the methodology are presented in this section based on the different road classifications.

Based on the Weslea software, the allowable number of load repetition to failure based on seasons in terms of fatigue life and rutting have been determined and presented in Table 12. Results for all the road classes shows that the pavement structure is more prone to rutting in the spring season with the least allowable number of load repetitions at this time. This is logical as in the spring season there is likely a high presence of water in the pavement structure due to the thawing of frozen water and rainfall. Fatigue cracking is also observed to occur more quickly in the summer season as the number of load repetition for this distress is the lowest at this period. This could be as a result of higher temperatures leading to softer asphalt surface layers. However, the allowable load repetitions have been found to be the highest in the winter allowing over 300 times more load repetition concerning rutting and 180 times more for fatigue compared to the spring and summer seasons respectively on major arterial roadways. This ratio is even higher for the highways, and a similar trend is noted for the other road classes. This means that the pavement structure is its most reliable in the winter.

The ESAL calculation for the Kenworth, Freightliner and Volvo vehicles for different truck configurations at various load percentages on the various road class are presented in Table 13 to 16. The parameters used in obtaining the ESALs are already described in the methodology with actual values also provided in Appendix E.

Considering the Freightliner vehicle on the highway, the expected ESAL at 100% load is observed to be greater for the 6 x 2 vehicle by 5%, 2%, and 3% at maximum, average, and minimum truck factors. However, the differences rise to 13%, 20%, and 4% at 85% load condition. This pattern is also true for the major arterial, minor arterial and collector roadways. Table 17 provides an overview of the ESAL differences between 6x2 and 6x4 on highway.

Table 12 The allowable number of load repetition to failure based on seasons

Road level	Season	Deterioration type	Allowable Number of Load Repetition
Highway	Winter	Fatigue	171,969,266
		Rutting	3,319,495,976
	Summer	Fatigue	907,370
		Rutting	64,352,781
	Spring	Fatigue	2,270,525
		Rutting	10,267,629
	Fall	Fatigue	3,478,168
		Rutting	110,603,838
Major Arterial	Winter	Fatigue	83,320,850
		Rutting	898,582,320
	Spring	Fatigue	1,104,634
		Rutting	2,696,734
	Summer	Fatigue	463,728
		Rutting	16,689,348
	Fall	Fatigue	1,725,750
		Rutting	29,054,458
Minor Arterial	Winter	Fatigue	26,909,485
		Rutting	104,895,503
	Spring	Fatigue	359,202
		Rutting	299,132
	Summer	Fatigue	171,859
		Rutting	1,862,131
	Fall	Fatigue	601,917
		Rutting	3,275,099
Collector	Winter	Fatigue	14,412,168
		Rutting	56,387,879
	Spring	Fatigue	203,852
		Rutting	179,286
	Summer	Fatigue	101,825
		Rutting	1,283,049
	Fall	Fatigue	343,231
		Rutting	2,063,603

Table 13 ESAL for different truck configurations at various load percentages on Highway

Road Class	Manufacturer	Configuration	Truck factor	Load Condition (%)				
				100	85	70	50	0
Highway	Kenworth	6×2	Maximum	-	12,999,840	6,972,595	3,840,165	1,098,650
		6×4		-	7,695,660	3,336,830	1,563,660	597,870
		6×2	Average	-	7,274,085	3,145,205	1,149,750	592,760
		6×4		-	5,416,600	2,721,075	1,190,630	564,655
		6×2	Minimum	-	5,378,275	2,253,510	853,370	531,440
		6×4		-	4,133,990	2,077,215	1,011,780	541,660
	Freightliner	6×2	Maximum	14,859,880	8,301,195	7,077,350	4,445,700	810,347
		6×4		14,126,595	7,340,515	4,374,160	1,596,875	692,405
		6×2	Average	12,608,925	7,092,680	4,139,100	1,849,820	668,782
		6×4		12,371,310	5,927,600	3,760,960	1,387,365	648,970
		6×2	Minimum	11,216,450	5,439,595	3,201,415	1,065,435	626,053
		6×4		10,912,405	5,245,415	3,244,850	1,200,850	628,530
	Volvo	6×2	Maximum	12,509,280	12,000,835	10,705,450	3,980,690	912,135
		6×4		11,764,299	7,289,415	1,297,940	1,650,530	648,970
		6×2	Average	10,753,995	6,326,180	5,087,005	2,626,540	794,605
		6×4		7,035,386	5,546,905	809,935	1,372,035	631,085
		6×2	Minimum	9,486,715	5,288,850	3,043,005	1,783,390	694,960
		6×4		615,672	3,418,590	636,195	1,188,075	618,310

Table 14 ESAL for different truck configurations at various load percentages on Major Arterial road

Road Class	Manufacturer	Configuration	Truck factor	Load Condition (%)				
				100	85	70	50	0
Major Arterial	Kenworth	6×2	Maximum	-	8,357,040	4,482,383	2,468,678	706,275
		6×4		-	4,947,210	2,145,105	1,005,210	384,345
		6×2	Average	-	4,676,198	2,021,918	739,125	381,060
		6×4		-	3,482,100	1,749,263	765,405	362,993
		6×2	Minimum	-	3,457,463	1,448,685	548,595	341,640
		6×4		-	2,657,565	1,335,353	650,430	348,210
	Freightliner	6×2	Maximum	9,552,780	5,336,483	4,549,725	2,857,950	520,937
		6×4		9,081,383	4,718,903	2,811,960	1,026,563	445,118
		6×2	Average	8,105,738	4,559,580	2,660,850	1,189,170	429,931
		6×4		7,952,985	3,810,600	2,417,760	891,878	417,195
		6×2	Minimum	7,210,575	3,496,883	2,058,053	684,923	402,463
		6×4		7,015,118	3,372,053	2,085,975	771,975	404,055
	Volvo	6×2	Maximum	8,041,680	7,714,823	6,882,075	2,559,015	586,373
		6×4		7,562,764	4,686,053	834,390	1,061,055	417,195
		6×2	Average	6,913,283	4,066,830	3,270,218	1,688,490	510,818
		6×4		4,522,748	3,565,868	520,673	882,023	405,698
		6×2	Minimum	6,098,603	3,399,975	1,956,218	1,146,465	446,760
		6×4		395,789	2,197,665	408,983	763,763	397,485

Table 15 ESAL for different truck configurations at various load percentages on Minor Arterial road

Road Class	Manufacturer	Configuration	Truck factor	Load Condition (%)				
				100	85	70	50	0
Minor Arterial	Kenworth	6×2	Maximum	-	1,253,556	672,357	370,302	105,941
		6×4		-	742,082	321,766	150,782	57,652
		6×2	Average	-	701,430	303,288	110,869	57,159
		6×4		-	522,315	262,389	114,811	54,449
		6×2	Minimum	-	518,619	217,303	82,289	51,246
		6×4		-	398,635	200,303	97,565	52,232
	Freightliner	6×2	Maximum	1,432,917	800,472	682,459	428,693	78,141
		6×4		1,362,207	707,835	421,794	153,984	66,768
		6×2	Average	1,215,861	683,937	399,128	178,376	64,490
		6×4		1,192,948	571,590	362,664	133,782	62,579
		6×2	Minimum	1,081,586	524,532	308,708	102,738	60,369
		6×4		1,052,268	505,808	312,896	115,796	60,608
	Volvo	6×2	Maximum	1,206,252	1,157,223	1,032,311	383,852	87,956
		6×4		1,134,415	702,908	125,159	159,158	62,579
		6×2	Average	1,036,992	610,025	490,533	253,274	76,623
		6×4		678,412	534,880	78,101	132,303	60,855
		6×2	Minimum	914,790	509,996	293,433	171,970	67,014
		6×4		59,368	329,650	61,347	114,564	59,623

Table 16 ESAL for different truck configurations at various load percentages on Collector

Road Class	Manufacturer	Configuration	Truck factor	Load Condition (%)				
				100	85	70	50	0
Collector	Kenworth	6×2	Maximum	-	464,280	249,021	137,149	39,238
		6×4		-	274,845	119,173	55,845	21,353
		6×2	Average	-	259,789	112,329	41,063	21,170
		6×4		-	193,450	97,181	42,523	20,166
		6×2	Minimum	-	192,081	80,483	30,478	18,980
		6×4		-	147,643	74,186	36,135	19,345
	Freightliner	6×2	Maximum	530,710	296,471	252,763	158,775	28,941
		6×4		504,521	262,161	156,220	57,031	24,729
		6×2	Average	450,319	253,310	147,825	66,065	23,885
		6×4		441,833	211,700	134,320	49,549	23,178
		6×2	Minimum	400,588	194,271	114,336	38,051	22,359
		6×4		389,729	187,336	115,888	42,888	22,448
	Volvo	6×2	Maximum	446,760	428,601	382,338	142,168	32,576
		6×4		420,154	260,336	46,355	58,948	23,178
		6×2	Average	384,071	225,935	181,679	93,805	28,379
		6×4		251,264	198,104	28,926	49,001	22,539
		6×2	Minimum	338,811	188,888	108,679	63,693	24,820
		6×4		21,988	122,093	22,721	42,431	22,083

Table 17 Overview of the ESAL differences between 6x2 and 6x4 on highway

Road Class	Manufacturer	Configuration	Truck factor	Load Condition (%)				
				100	85	70	50	0
Highway	Kenworth	6×2 6×4	Maximum	-	69%	109%	146%	84%
		6×2 6×4	Average	-	34%	16%	-3%	5%
		6×2 6×4	Minimum	-	30%	8%	-16%	-2%
	Freightliner	6×2 6×4	Maximum	5%	13%	62%	178%	17%
		6×2 6×4	Average	2%	20%	10%	33%	3%
		6×2 6×4	Minimum	3%	4%	-1%	-11%	0%
	Volvo	6×2 6×4	Maximum	6%	65%	725%	141%	41%
		6×2 6×4	Average	53%	14%	528%	91%	26%
		6×2 6×4	Minimum	1441%	55%	378%	50%	12%

4.3.1 Fatigue Cracking Summary

The damage ratio induced by these vehicles based on the calculated ESALs for maximum, average and minimum truck factor values at different load percentage over ten years has been analyzed in this study and details provided in Appendix B. A summary for fatigue cracking damage induced in the first year by the different vehicles at the average truck factor values is presented in Table 19. All the values are ratios with a ratio above one signifying that the damage caused has exceeded its allowable load capacity. By year one, highway and major arterial roads experienced fatigue cracking with damage ratios above one except some instance at 50% and 0% load levels. Minor arterial road and collector experienced fatigue cracking at 85% load and above in year one.

Table 18 demonstrates the percentage differences for fatigue cracking and rutting between 6x2 and 6x4 vehicles. It is clear that 6x2 vehicles exhibited higher damage ratio than 6x4 vehicles in all load condition with average truck factor except for the KW 50% load condition. In Canada the weight limit for tandem axle set on tractor semitrailers on the designated highway system is 17,000kg, represented by the "85% load condition" in this study. At 85% load condition with average truck factor, 6x2 vehicles exerted 14% to 34% greater damage ratios than 6x4 vehicles. At 100% load, the difference becomes 2% for FL vehicles.

4.3.2 Rutting Summary

A summary of rutting damage induced in the first year by the different vehicles at the average truck factor values is presented in Table 20. Like the fatigue damage, all values are ratios with a ratio above one signifying that the damage induced has exceeded the required limit. Generally, for all road classes and load levels, the damage ratio induced by the vehicle brands and types remained below one. This means that these vehicles did not cause rutting failures at year one. However, from year two, rutting damage starts to occur for the 100% load levels and after five years for the other load levels. The damage ratio is lowest for the highway compared to other road classes. Table 18 shows the percentage differences for rutting between 6x2 and 6x4 vehicles, with 6x2 vehicles exhibiting higher damage in most cases. It is noted that the magnitude of the difference in damage caused by 6 x 2 compared to the 6 x 4 vehicle is high for the Volvo truck especially at 70% and 50% load for all road classes.

Table 18 Differences of damage ratio for fatigue cracking and rutting between 6x2 and 6x4 vehicles with average truck factor

Road level	Manufacturer	Configuration	Damage ratio (1st year)				
			100% Load	85% Load	70% Load	50% Load	0% Load
Highway	KW	6×2 6×4	-	34%	16%	-3%	5%
	FL	6×2 6×4	2%	20%	10%	33%	3%
	VV	6×2 6×4	53%	14%	528%	91%	26%
Major Arterial	KW	6×2 6×4	-	34%	16%	-3%	5%
	FL	6×2 6×4	2%	20%	10%	33%	-
	VV	6×2 6×4	-	14%	528%	91%	26%
Minor Arterial	KW	6×2 6×4	-	34%	16%	-3%	5%
	FL	6×2 6×4	2%	20%	10%	33%	3%
	VV	6×2 6×4	53%	14%	528%	91%	26%
Collector	KW	6×2 6×4	-	34%	16%	-3%	5%
	FL	6×2 6×4	2%	20%	10%	33%	3%
	VV	6×2 6×4	53%	14%	528%	91%	26%

Table 19 Fatigue cracking damage ratio (first year) at the average truck factor values

Road level	Manufacturer	Configuration	Damage ratio (1st year)				
			100% Load	85% Load	70% Load	50% Load	0% Load
Highway	KW	6×2	-	2.90	1.26	0.46	0.24
		6×4	-	2.16	1.09	0.48	0.23
	FL	6×2	5.03	2.83	1.65	0.74	0.27
		6×4	4.94	2.37	1.50	0.55	0.26
	VV	6×2	4.29	2.53	2.03	1.05	0.32
		6×4	2.81	2.21	0.32	0.55	0.25
Major Arterial	KW	6×2	-	3.70	1.60	0.59	0.30
		6×4	-	2.76	1.38	0.61	0.29
	FL	6×2	6.42	3.61	2.11	0.94	0.34
		6×4	6.30	3.02	1.91	0.71	0.33
	VV	6×2	5.47	3.22	2.59	1.34	0.40
		6×4	3.58	2.82	0.41	0.70	0.32
Minor Arterial	KW	6×2	-	1.55	0.67	0.25	0.13
		6×4	-	1.15	0.58	0.25	0.12
	FL	6×2	2.69	1.51	0.88	0.39	0.14
		6×4	2.64	1.26	0.80	0.30	0.14
	VV	6×2	2.29	1.35	1.08	0.56	0.17
		6×4	1.50	1.18	0.17	0.29	0.13
Collector	KW	6×2	-	0.98	0.43	0.16	0.08
		6×4	-	0.73	0.37	0.16	0.08
	FL	6×2	1.71	0.96	0.56	0.25	0.09
		6×4	1.67	0.80	0.51	0.19	0.09
	VV	6×2	1.45	0.86	0.69	0.36	0.11
		6×4	0.95	0.75	0.11	0.19	0.09

Table 20 Rutting damage ratio (first year) at the average truck factor values

Road level	Manufacturer	Configuration	Damage ratio (1st year)				
			100% Load	85% Load	70% Load	50% Load	0% Load
Highway	KW	6×2	-	0.16	0.07	0.03	0.01
		6×4	-	0.12	0.06	0.03	0.01
	FL	6×2	0.27	0.15	0.09	0.04	0.01
		6×4	0.27	0.13	0.08	0.03	0.01
	VV	6×2	0.23	0.14	0.11	0.06	0.02
		6×4	0.15	0.12	0.02	0.03	0.01
Major Arterial	KW	6×2	-	0.39	0.17	0.06	0.03
		6×4	-	0.29	0.15	0.06	0.03
	FL	6×2	0.67	0.38	0.22	0.10	0.04
		6×4	0.66	0.32	0.20	0.07	0.03
	VV	6×2	0.57	0.34	0.27	0.14	0.04
		6×4	0.38	0.30	0.04	0.07	0.03
Minor Arterial	KW	6×2	-	0.52	0.23	0.08	0.04
		6×4	-	0.39	0.20	0.09	0.04
	FL	6×2	0.91	0.51	0.30	0.13	0.05
		6×4	0.89	0.43	0.27	0.10	0.05
	VV	6×2	0.77	0.46	0.37	0.19	0.06
		6×4	0.51	0.40	0.06	0.10	0.05
Collector	KW	6×2	-	0.32	0.14	0.05	0.03
		6×4	-	0.23	0.12	0.05	0.02
	FL	6×2	0.55	0.31	0.18	0.08	0.03
		6×4	0.54	0.26	0.16	0.06	0.03
	VV	6×2	0.47	0.27	0.22	0.11	0.03
		6×4	0.30	0.24	0.04	0.06	0.03

4.3.3 Worst-Case Scenario in Flexible pavement

The above section summarizes the failure criteria analysis of the 6x2 and 6x4 trucks under the circumstances with an average truck factor. However, it should be noted that 6x2 configuration may have higher damage ratio when the slippery condition occurs. Figure 8 demonstrates one of the examples of this situation. The scenario is set to be on Highway Road Levels with 85% and 100% load for 6x2 and 6x4. It is clear that at the worst scenario when using max tf in the analysis, the 6x2 configuration has the highest damage ratio compared to others. The difference between the two configuration trucks could be smaller for some manufacturers. For instance, the difference in the damage ratios between 6x2 and 6x4 Freightliner trucks is reduced at 100% load condition.

However, Volvo's 6x2 trucks have significantly higher damage ratio at 85% load max tf compared to 6x4 trucks. Appendix B provides all the damage ratio figures for reference.

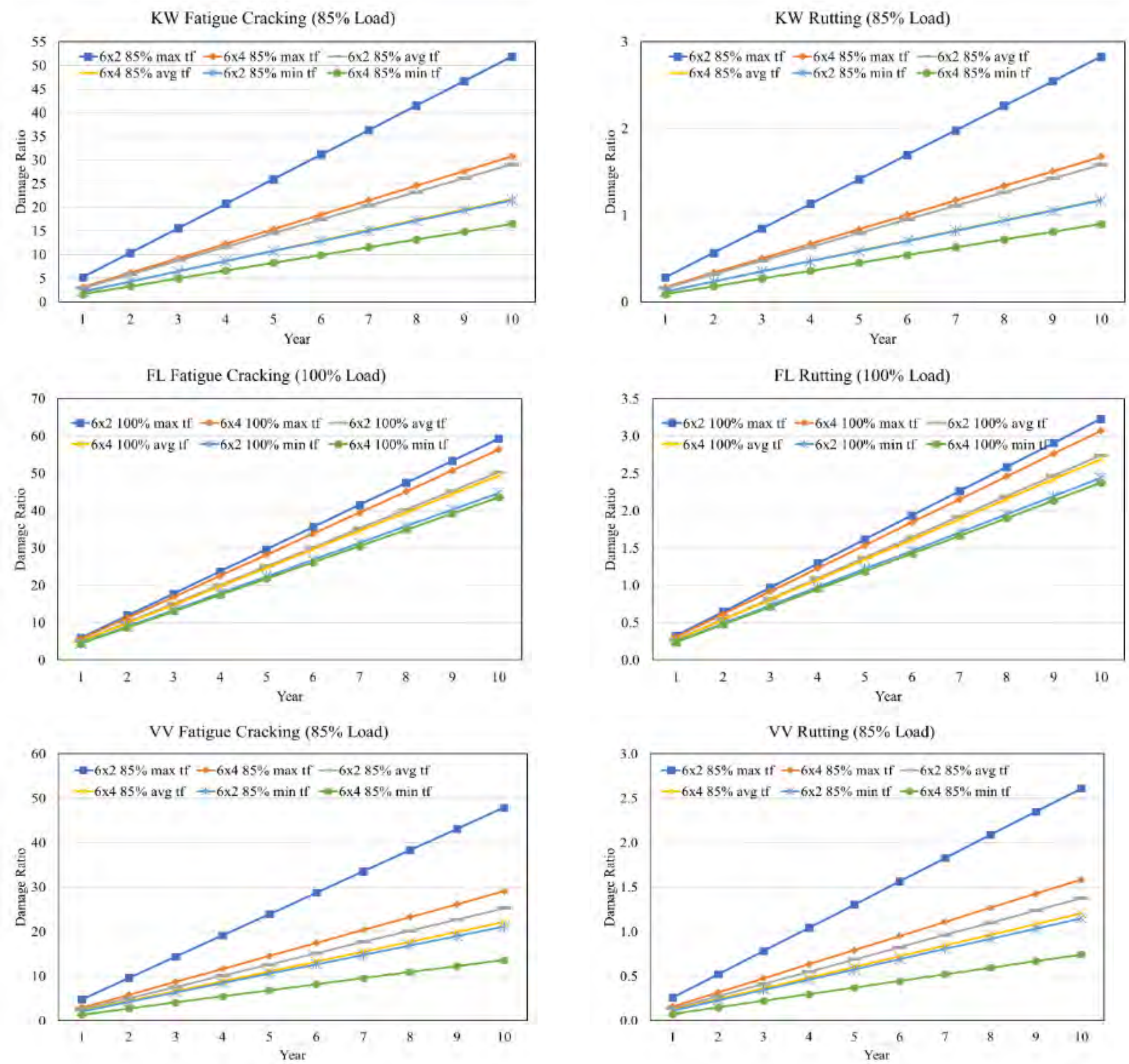

Figure 8 Damage Ratio at higher load percentages on highway

4.4 Gravel Road

Damage analysis for gravel road for all the vehicle brands and types at different load levels are presented in this section. The damage analysis is based on the serviceability and rutting criteria as earlier described with as serviceability loss (ΔPSI) of 2.0 and allowable rutting depth of 5cm (2inch).

Kenworth (KW)

The ESAL calculation for the Kenworth vehicle for different truck types and load percentages is presented in Table 21. The expected ESAL for maximum, average and minimum truck factor at 85% load is observed to be greater for the 6 x 2 than 6 x 4 vehicle by 69%, 34% and 30% respectively.

Table 21 ESAL for the Kenworth vehicle for different truck types at 85% load condition

Industry	Configuration	AADTT	Day	growth(0%)	DSF	LD	TF	years	ESAL
KW	**6x2 85% max tf**	50	365	1	0.5	0.7	5.088	1	32,500
	6x4 85% max tf	50	365	1	0.5	0.7	3.012	1	19,239
	6x2 85% avg tf	50	365	1	0.5	0.7	2.847	1	18,185
	6x4 85% avg tf	50	365	1	0.5	0.7	2.12	1	13,542
	6x2 85% min tf	50	365	1	0.5	0.7	2.105	1	13,446
	6x4 85% min tf	50	365	1	0.5	0.7	1.618	1	10,335

Freightliner (FL)

The ESAL calculation for the Freightliner vehicle for different truck types and load percentages is presented in Table 22. The expected ESAL of maximum, average and minimum truck factor at 100% load is observed to be greater for the 6 x 2 than 6 x 4 vehicle by 5%, 2% and 3% respectively.

Table 22 ESAL for the Freightliner vehicle for different truck types at 100% load condition

Industry	Configuration	AADTT	Day	growth(0%)	DSF	LD	TF	years	ESAL
FL	**6x2 100% max tf**	50	365	1	0.5	0.7	5.816	1	37,150
	6x4 100% max tf	50	365	1	0.5	0.7	5.529	1	35,316
	6x2 100% avg tf	50	365	1	0.5	0.7	4.935	1	31,522
	6x4 100% avg tf	50	365	1	0.5	0.7	4.842	1	30,928
	6x2 100% min tf	50	365	1	0.5	0.7	4.39	1	28,041
	6x4 100% min tf	50	365	1	0.5	0.7	4.271	1	27,281

Volvo (VV)

The ESAL calculation for the Volvo vehicle for different truck types and load percentages is presented in Table 23. The expected ESAL of maximum, average and minimum truck factor at 85% load is observed to be greater for the 6 x 2 than 6 x 4 vehicle by 65%, 14% and 55% respectively.

Table 23 ESAL for the Volvo vehicle for different truck types at 85% load condition

Industry	Configuration	AADTT	Day	Growth (0%)	DSF	LD	TF	years	ESAL
VV	**6x2 85% max tf**	50	365	1	0.5	0.7	4.697	1	30,002
	6x4 85% max tf	50	365	1	0.5	0.7	2.853	1	18,224
	6x2 85% avg tf	50	365	1	0.5	0.7	2.476	1	15,815
	6x4 85% avg tf	50	365	1	0.5	0.7	2.171	1	13,867
	6x2 85% min tf	50	365	1	0.5	0.7	2.07	1	13,222
	6x4 85% min tf	50	365	1	0.5	0.7	1.338	1	8,546

4.4.1 Gravel Road minimum thickness summary

Table 24 and 25 demonstrates the summary of gravel road minimum thickness using avg tf. At 50% or lower load condition, the minimum thickness appears to be the same for both vehicles, indicating that the 6x2 vehicle has a similar impact as the 6x4 vehicle on the gravel road. However, at 70% load Volvo 6x2 vehicle will require thicker pavement to meet the rutting criteria, this is due the fact that Volvo 6x2 has a higher truck factor and damage ratio compared with the 6x4 vehicle. When considering 85% load condition, 6x2 vehicles from all manufacturers need at least 254 mm pavement thickness, while 6x4 vehicles require 229 mm thickness, this means, it would induce more damage than 6x4 vehicles. At 100% load, the thickness for both Freightliner vehicle are the same, which is 330 mm thick.

In the case of 85% load, for serviceability and rutting, the 6 x 2 vehicles at all truck factor levels required more pavement thickness As the load levels reduce to 70%, 50% and 0%, the intensity of the damage induced by 6 x 2 and 6 x 4 vehicles reduce and showed minimal difference. As a result, similar pavement thicknesses are required, except for the max tf of the 6 x 2 vehicle whose damage remained most times significantly higher than its comparable 6 x 4 vehicle.

Table 24 Summary of Gravel Road minimum thickness using avg tf (Serviceability)

Road level	Manufacturer	Configuration	Minimum Thickness (Damage Ratio)				
			100% Load	85% Load	70% Load	50% Load	0% Load
Gravel Road	KW	6×2	-	229 (0.93)	178 (0.69)	178 (0.25)	178 (0.13)
		6×4	-	203 (0.90)	178 (0.60)	178 (0.26)	178 (0.12)
	FL	6×2	279 (0.94)	229 (0.91)	178 (0.91)	178 (0.41)	178 (0.15)
		6×4	279 (0.92)	203 (0.98)	178 (0.83)	178 (0.31)	178 (0.14)
	VV	6×2	254 (0.97)	229 (0.81)	203 (0.85)	178 (0.58)	178 (0.18)
		6×4	229 (0.90)	203 (0.92)	178 (0.18)	178 (0.30)	178 (0.14)

Table 25 Summary of Gravel Road minimum thickness using avg tf (Rutting)

Road level	Manufacturer	Configuration	Minimum Thickness (Damage Ratio)				
			100% Load	85% Load	70% Load	50% Load	0% Load
Gravel Road	KW	6×2	-	254 (0.90)	178 (0.92)	178 (0.34)	178 (0.17)
		6×4	-	229 (0.87)	178 (0.80)	178 (0.35)	178 (0.17)
	FL	6×2	330 (0.93)	254 (0.88)	203 (0.99)	178 (0.54)	178 (0.20)
		6×4	330 (0.91)	229 (0.95)	203 (0.91)	178 (0.41)	178 (0.19)
	VV	6×2	305 (0.94)	254 (0.79)	229 (0.82)	178 (0.77)	178 (0.23)
		6×4	254 (0.87)	229 (0.89)	178 (0.24)	178 (0.40)	178 (0.19)

4.4.2 Worst-Case Scenario in Gravel Road

An example of the damage ratio for gravel road is presented in Figure 9. Similar to the damage ratio trend in the flexible pavement, Freightliner's 6x2 has comparable damage ratio with the 6x4 trucks at 100% load condition. However, Kenworth and Volvo 6x2 truck have higher damage ratio for max tf scenario at 85% load condition, which, results in thicker pavement design in this case. Appendix B provides all the damage ratio figures for reference.

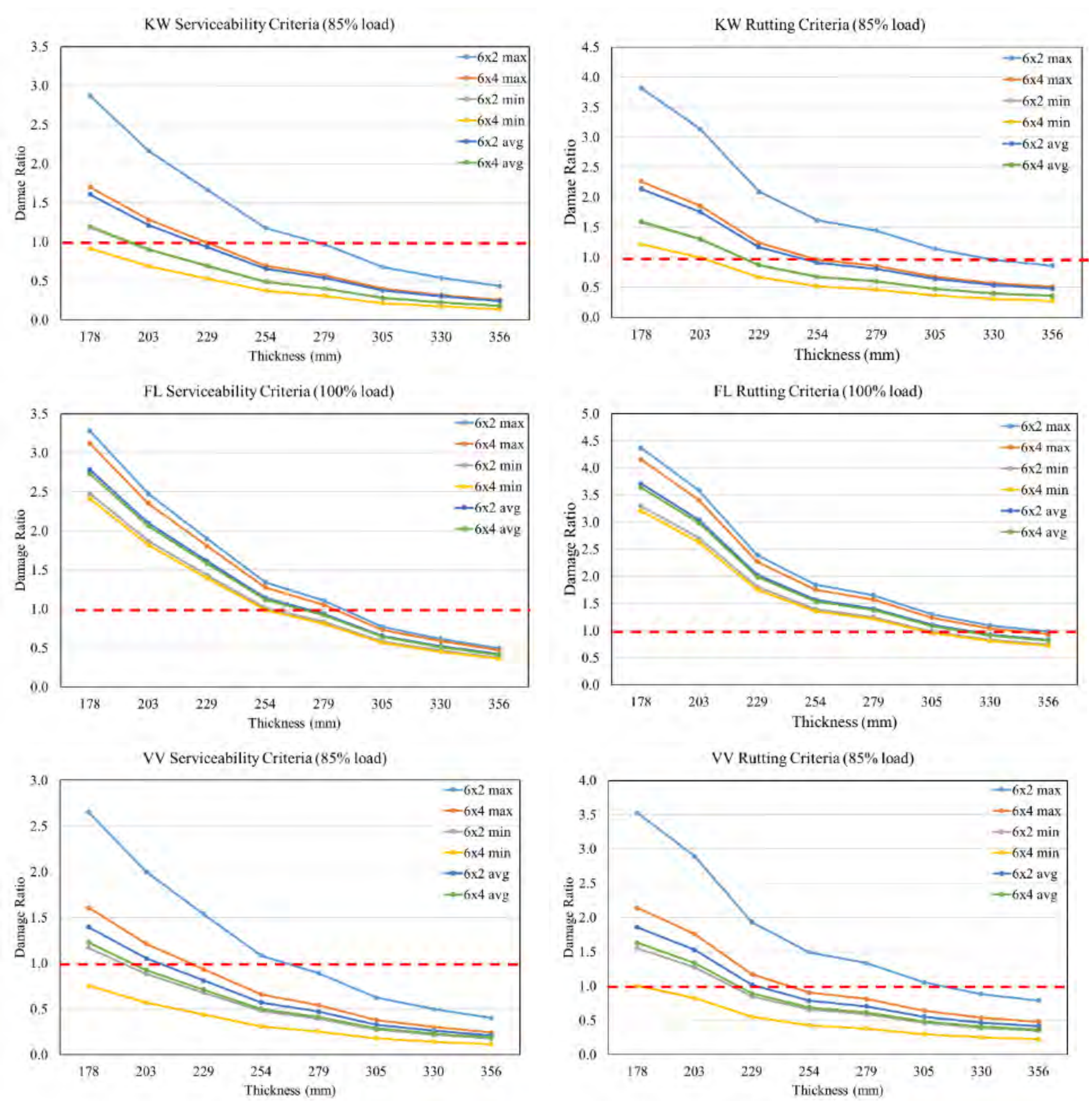

Figure 9 Damage Ratio at higher load percentages on gravel road

5.0 Conclusions

In this study, the potential impact of the 6x2 configuration vehicles on road pavement for different road classes has been evaluated. This impact has been compared with the existing 6x4 vehicle effects. Track test data has been acquired from the National Research Council (NRC) to perform statistical and damage ratio analysis. In order to understand the typical road pavement infrastructure that 6x2 vehicles are expected to use in Canada, a Survey has been carried out to obtain information from professionals in most jurisdictions. The survey results depict that pavement thickness for most regions, for flexible pavement were quite similar. The expected road level that 6 x 2 vehicles are expected to travel varies from province to province with some provinces indicating use on only Urban roadways while others signify both Rural and Urban.

The statistical analysis for truck factor shows that the Kenworth and Freightliner 6x2 vehicles have similar average truck factors as their 6x4 vehicles at load levels equal or below 70%. At a higher load level, the Volvo 6x2 vehicle have a similar average truck factor as the Volvo 6x4 vehicle.

The results of damage ratio analysis of the 6x2 and 6x4 vehicles for flexible pavement at year one shows that most of the roads experienced fatigue cracking with damage ratios above one except some instance at 50% and 0% load levels. For rutting criteria of all the road class and load levels, the damage ratio induced by the vehicles remained below one. This means that these vehicles did not cause rutting failures at year one. Yet the trend of the level of damage still followed the same pattern in fatigue cracking. The truck factor played an important role in evaluating the level of damage for different road classes, from the percentage differences for fatigue cracking and rutting between 6x2 and 6x4 vehicles. The 6x2 vehicles demonstrate greater damage ratio than the 6x4 vehicles in all load conditions with average truck factor except for the KW 50% load condition.

For gravel roads, truck factor played a significant role in serviceability and rutting damage ratio analysis as it is the main parameter that is differing to calculate the ESAL. For example, the 6x2 vehicles require thicker pavement layer than 6x4 vehicles at 85% load using average truck factor. But at 70% and lower load condition, the required pavement thickness for 6x2 vehicles and the 6x4 vehicles are the same except in the case of Volvo.

Worst-case scenarios for both flexible pavement and gravel road have been examined. The worst-case scenario is set to assume the truck is running using max tf as it is running during load shifting event at all time. Results shows that the 6x2 configurations have higher damage ratios when slippery conditions occur. The difference between the two configuration trucks could be reduced for some manufacturers. It is clear that at the worst scenario when using max tf in the analysis, 6x2 configuration has the highest damage ratio compared to 6x4 configuration.

In Canada the weight limit for tandem axle sets on tractor semitrailers on the designated highway system is 17,000kg, represented by the “85% load condition” in this study. Using average truck factors from the NRC Dynamic Axle Load Test (Chuang, 2018), the analysis showed that at 85% load the damage ratios are 14% to 34% greater for the 6x2 vehicles compared to their 6x4 counterparts. At 70% or lower load conditions, for most cases the damage ratios are 5% to 33% higher for the 6x2 vehicles compared to the 6x4 counterparts.

It should be noted that when there is no load biasing event (e.g. no low traction trigger), infrastructure impacts should be equivalent for 6x2 and 6x4 configurations. A limitation of this study is that there was a lack of real world data on the frequency and locations of low traction triggers (e.g. ice patches), therefore the analysis is based on the "NRC dynamic axle load test" (Chuang, 2018) in which the vehicles start on an ice patch, thus triggering a load biasing event, and continue accelerating up to 80 km/h on dry pavement. When applied to data from this test, the analysis represents a scenario where vehicles repeatedly lose traction in the same location. This would represent a particularly challenging scenario for infrastructure.

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Appendix A

Truck factor of each vehicle under different loading condition

Table Truck factor of each vehicle under different loading condition

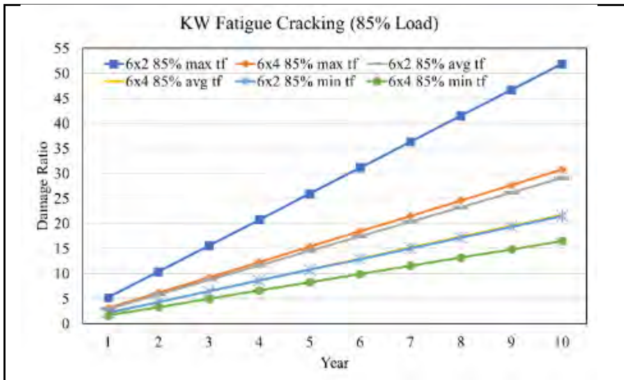
Test	Vehicle	Model	Load(%)	Cycle	TF.avg	TF.max	TF.min
H	F	A	0	1	0.254	0.271	0.246
H	F	A	50	1	0.543	0.625	0.47
H	F	A	70	1	1.472	1.712	1.27
H	F	A	85	1	2.32	2.873	2.053
H	F	A	100	1	4.842	5.529	4.271
H	F	B	50	1	0.724	1.74	0.417
H	F	B	70	1	1.62	2.77	1.253
H	F	B	85	1	2.776	3.249	2.129
H	F	B	100	1	4.935	5.816	4.39
H	K	A	0	1	0.221	0.234	0.212
H	K	A	50	1	0.466	0.612	0.396
H	K	A	70	1	1.065	1.306	0.813
H	K	A	85	1	2.12	3.012	1.618
H	K	A	100	1	4.68	5.385	4.247
H	K	B	0	1	0.232	0.43	0.208
H	K	B	50	1	0.45	1.503	0.334
H	K	B	70	1	1.231	2.729	0.882
H	K	B	85	1	2.847	5.088	2.105
H	K	B	100	1	3.296	5.837	2.099
H	V	A	0	1	0.247	0.254	0.242
H	V	A	50	1	0.537	0.646	0.465
H	V	A	70	1	0.317	0.508	0.249
H	V	A	85	1	2.171	2.853	1.338
H	V	B	0	1	0.311	0.357	0.272
H	V	B	50	1	1.028	1.558	0.698
H	V	B	70	1	1.991	4.19	1.191
H	V	B	85	1	2.476	4.697	2.07
H	V	B	100	1	4.209	4.896	3.713

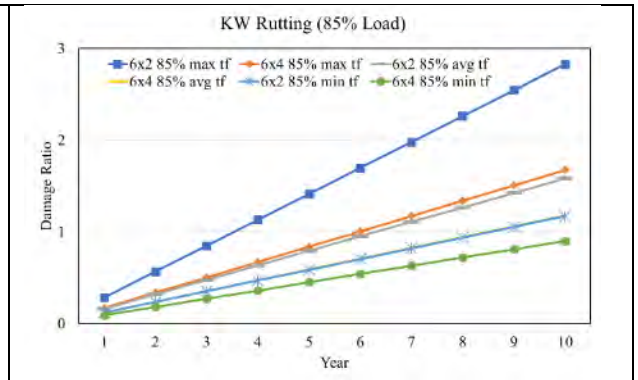
Appendix B

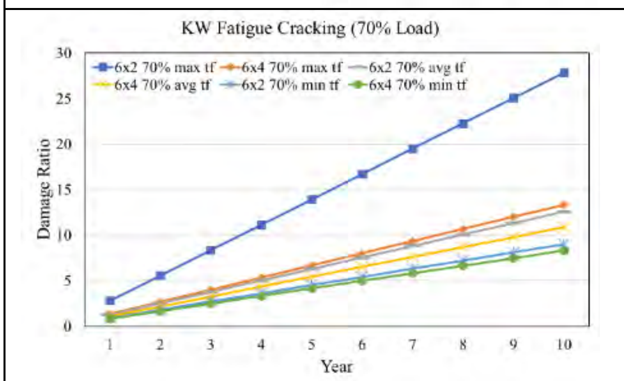
Result of Damage Ratio

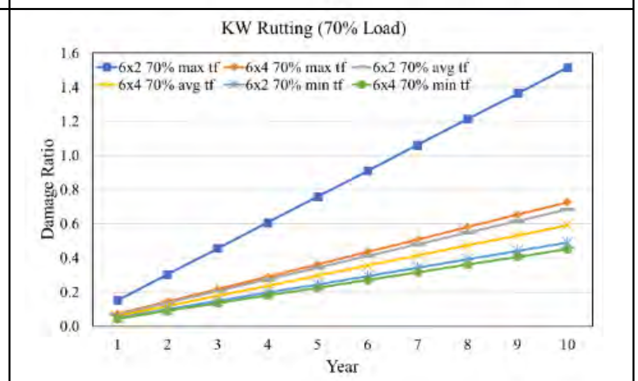
Highway

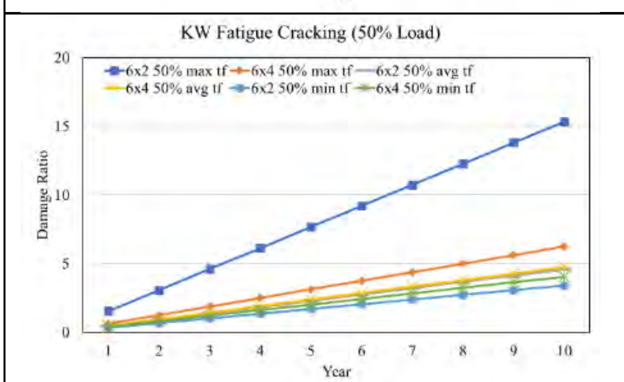
Kenworth (KW)

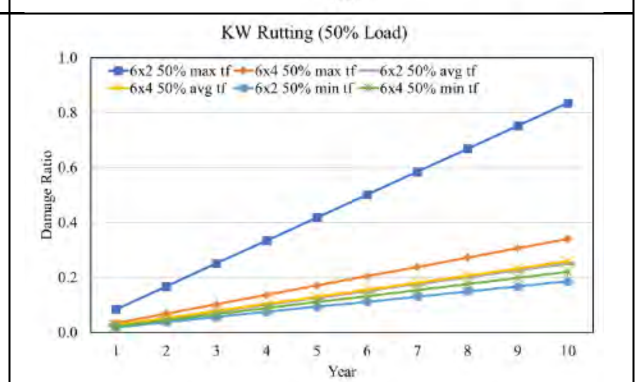


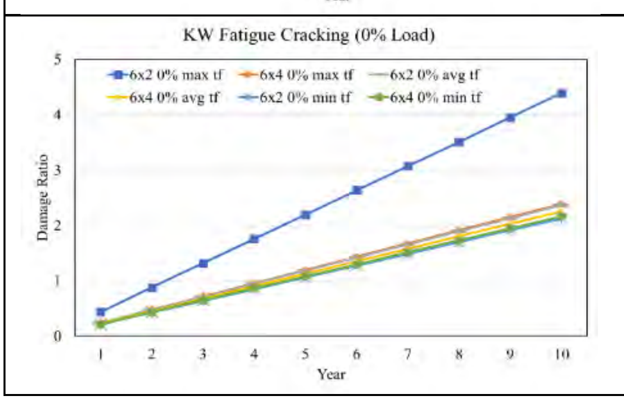


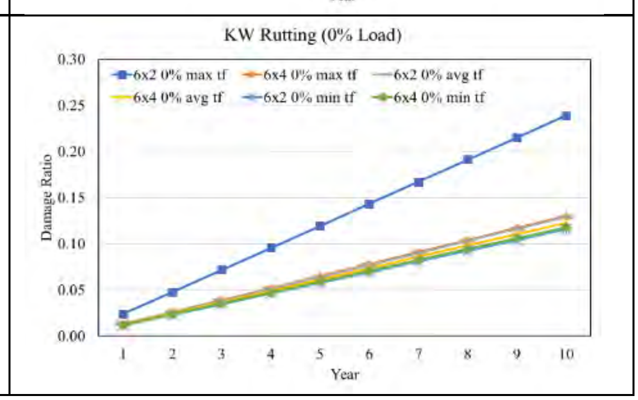




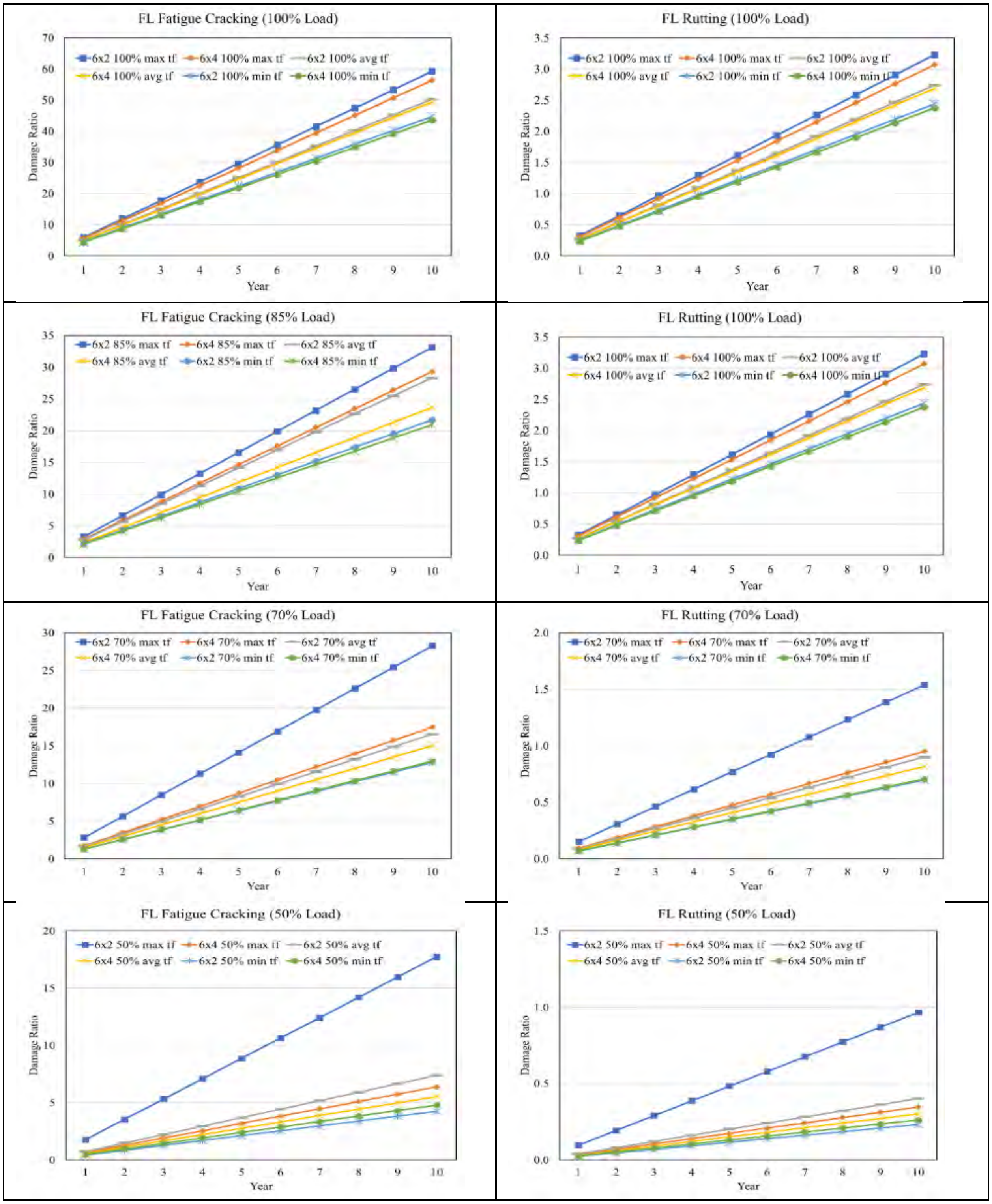


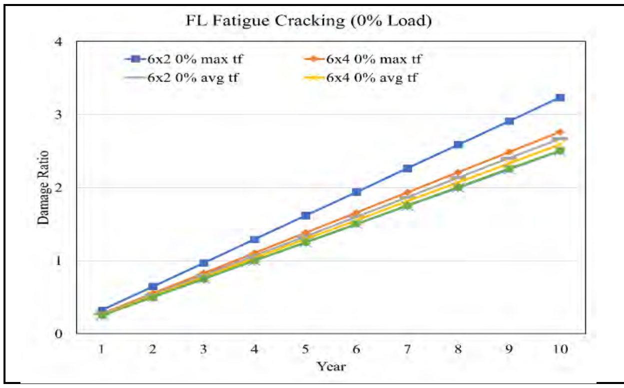






Frieghtliner (FL)

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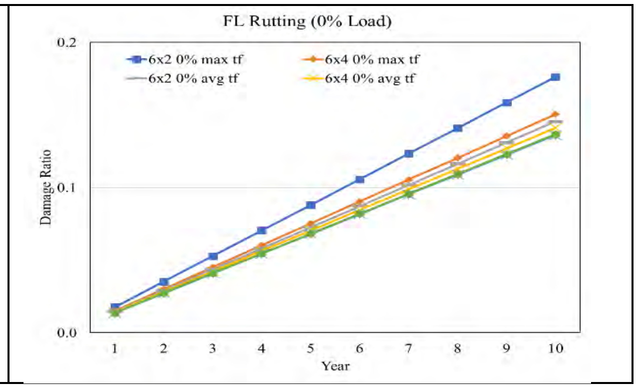
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
Damage Ratio
Year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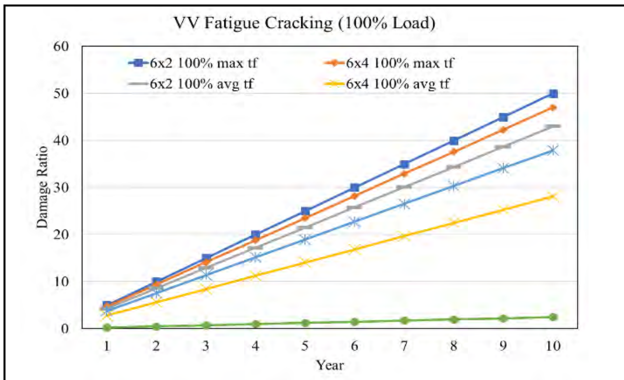
Damage Ratio
Year

Volvo (VV)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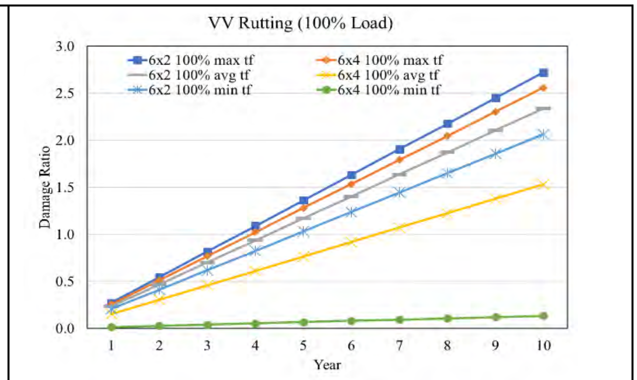
Damage Ratio
Year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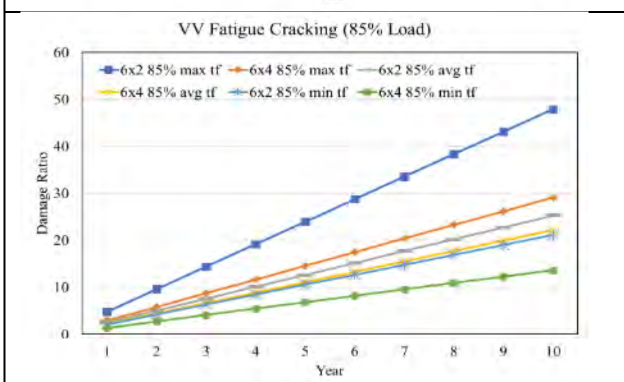
6x4 100% min tf
Damage Ratio
Year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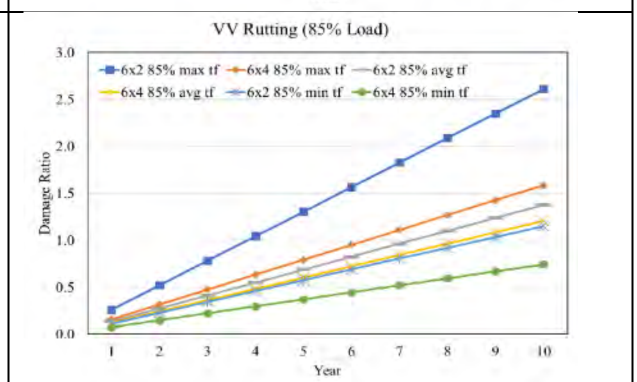
Damage Ratio
Year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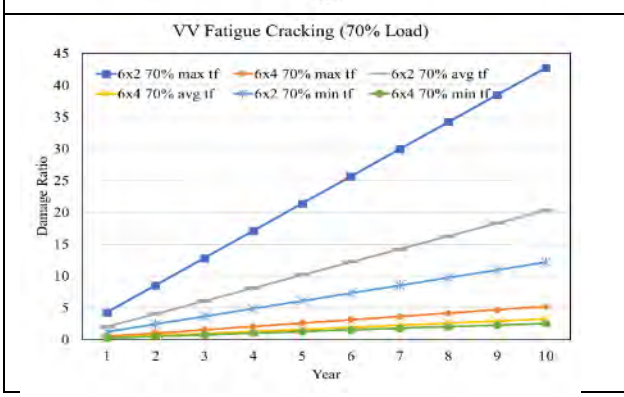
Damage Ratio
Year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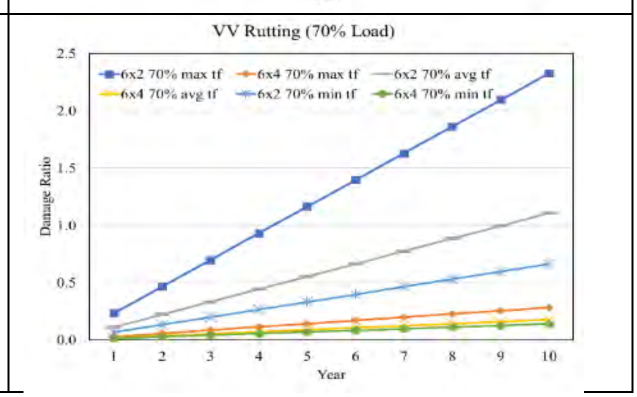
Damage Ratio
Year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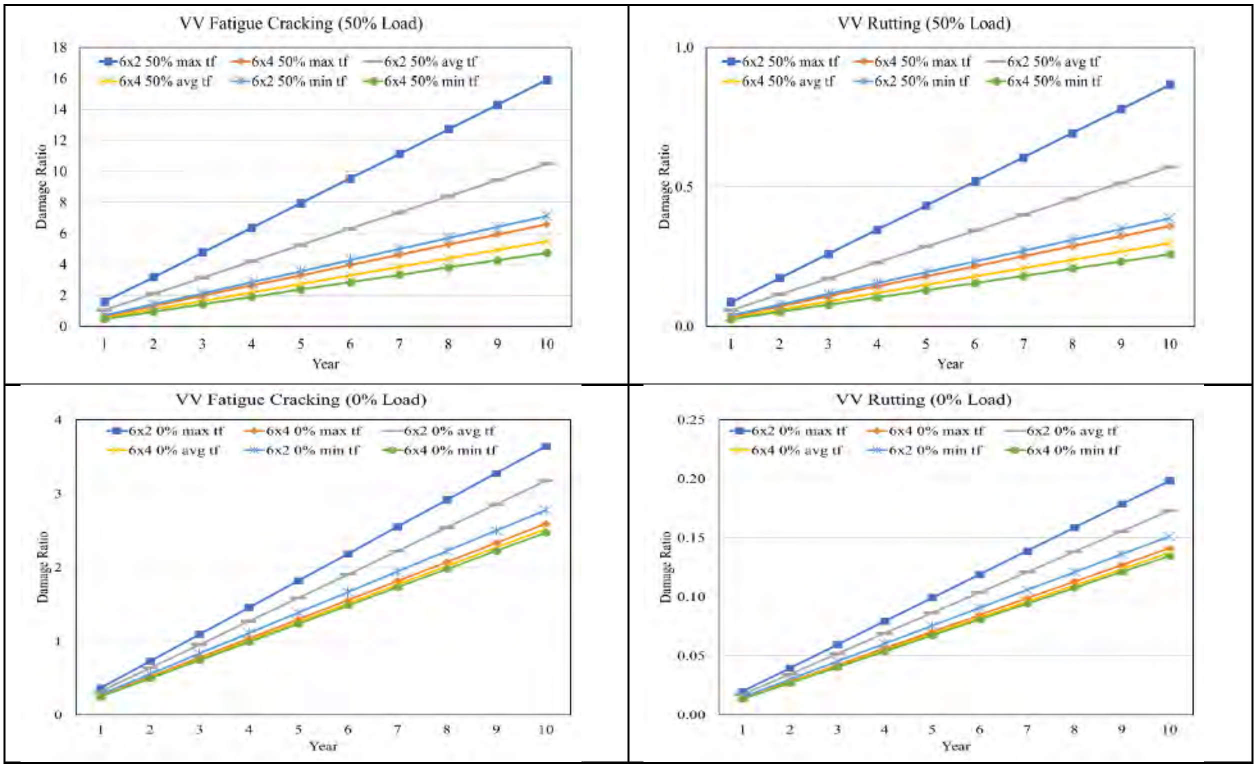
Damage Ratio
Year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Damage Ratio
Year
VV Rutting (50% Load)
6x2 50% max tf
6x4 50% max tf
6x2 50% avg tf
6x4 50% avg tf
6x2 50% min tf
6x4 50% min tf
Damage Ratio
Year
VV Fatigue Cracking (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year
VV Rutting (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
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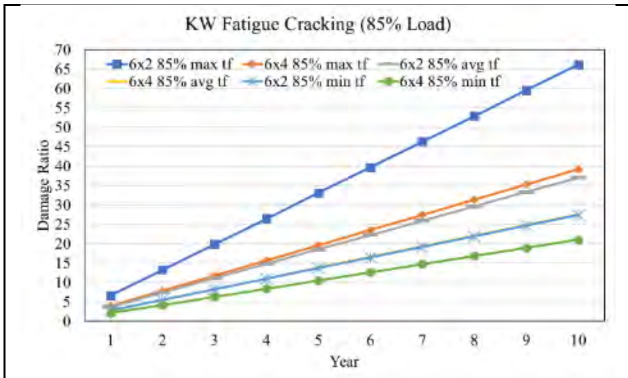
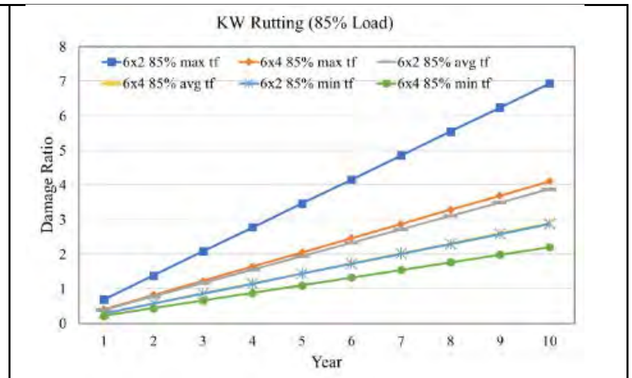
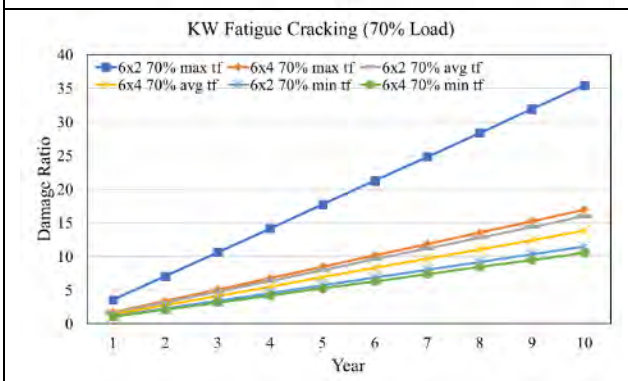
Damage Ratio
Year

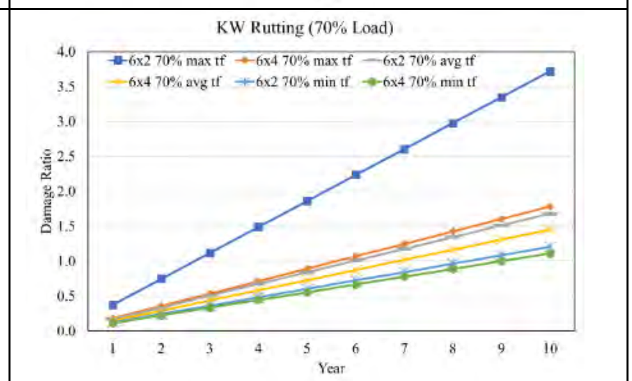
Major Arterial Road

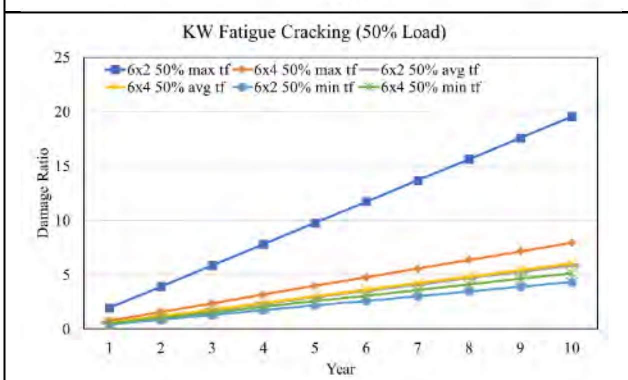
Kenworth (KW)

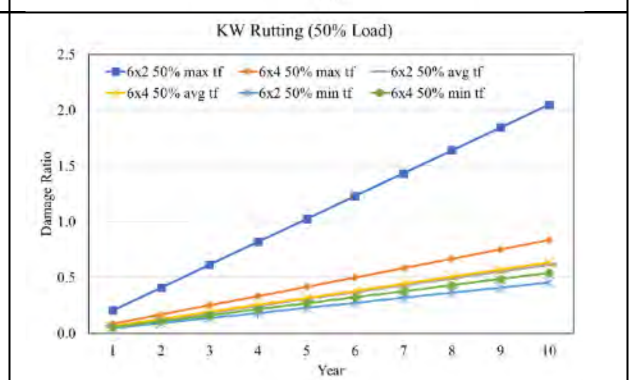


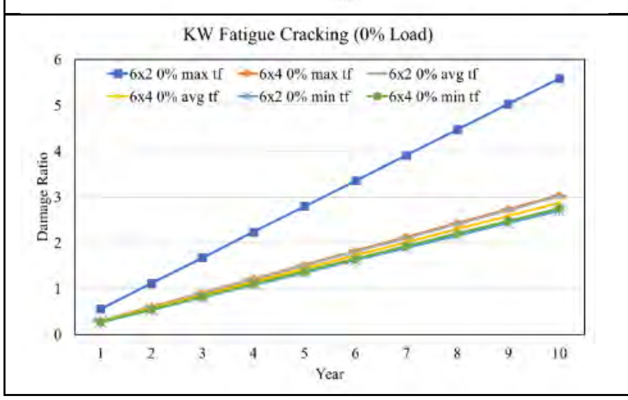


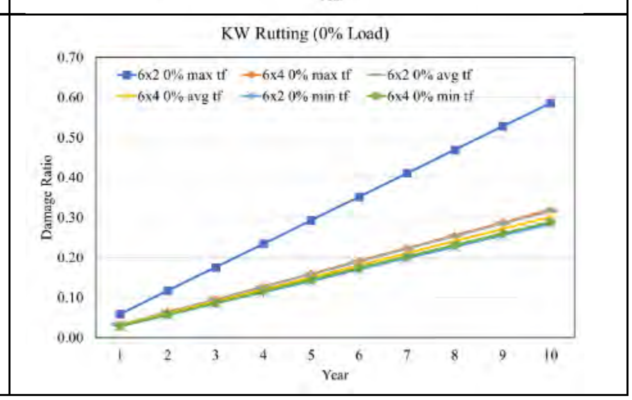












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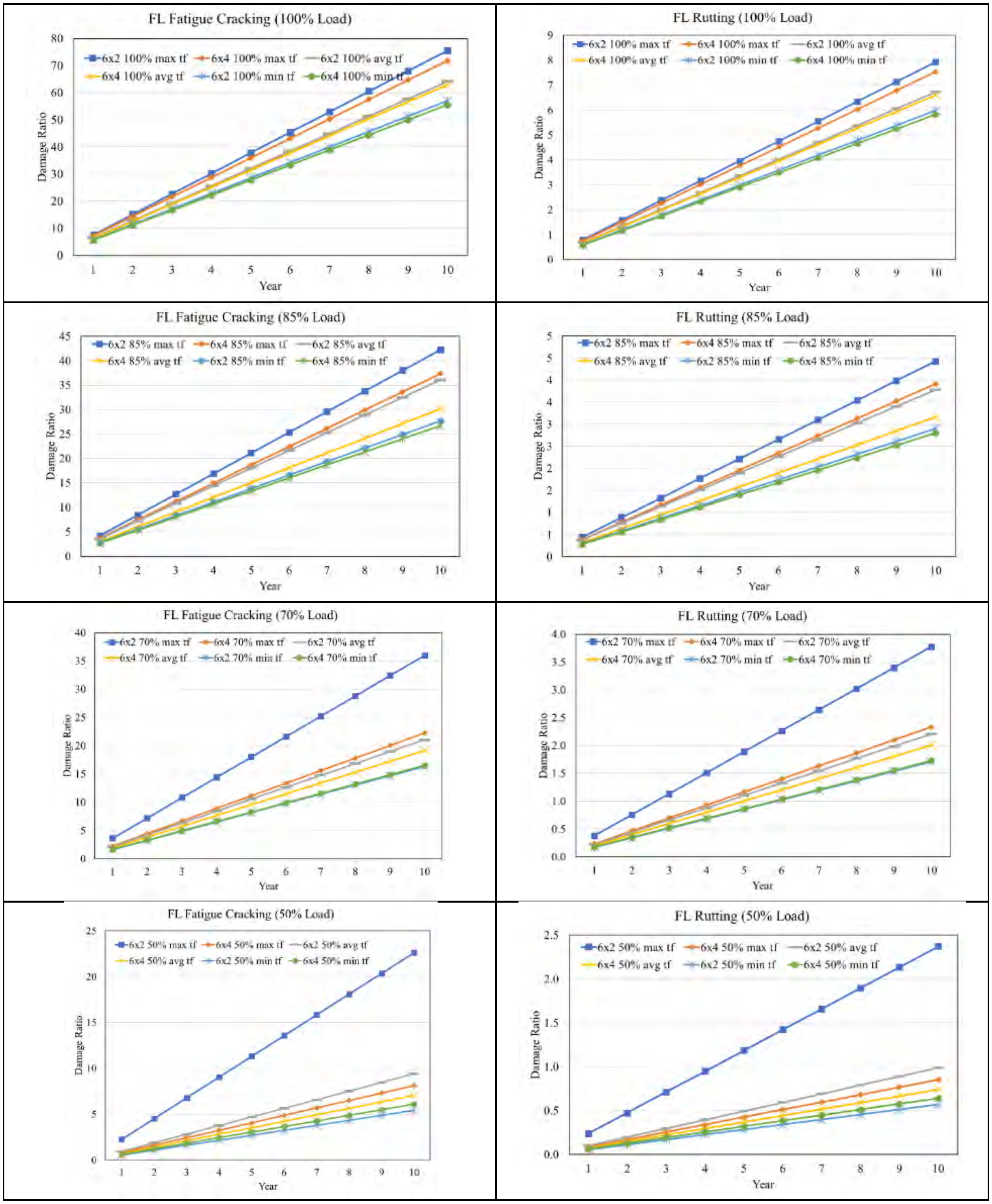

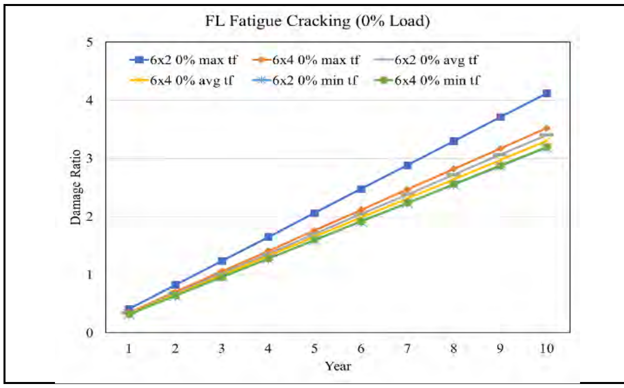
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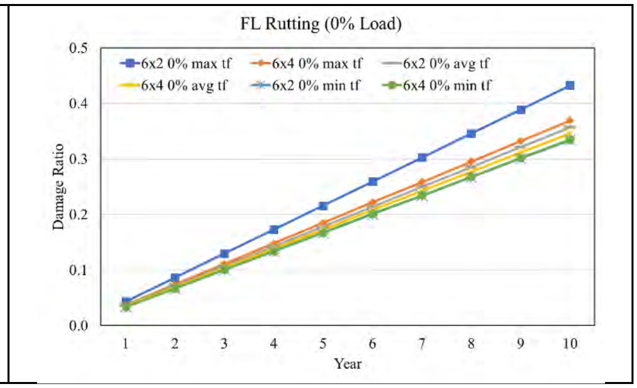
Damage Ratio
Year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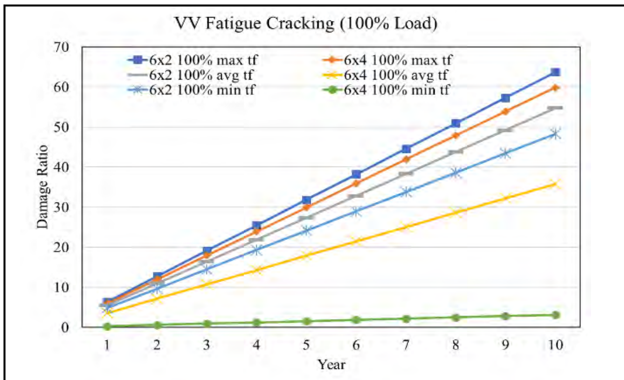
Damage Ratio
Year

Volvo (VV)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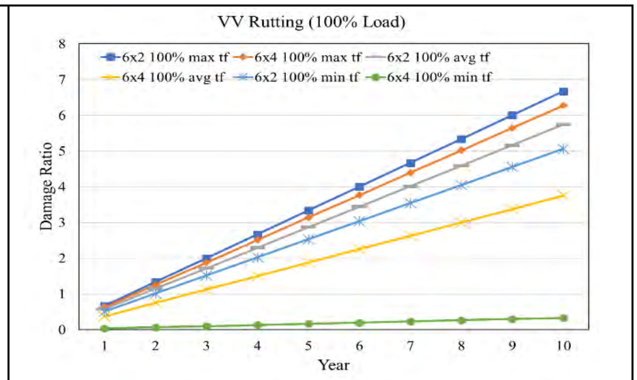
Damage Ratio
Year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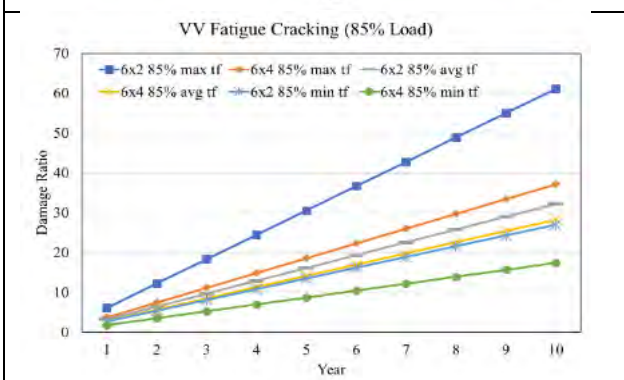
Damage Ratio
Year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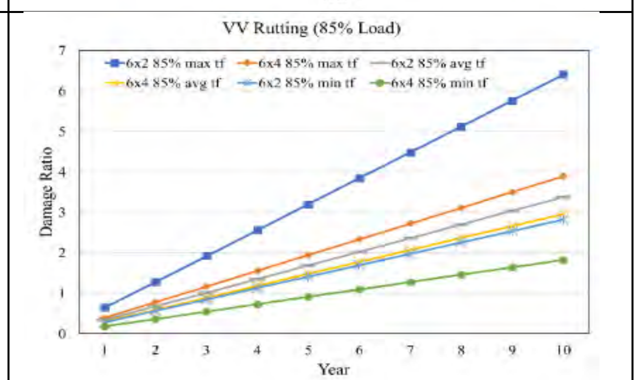
Damage Ratio
Year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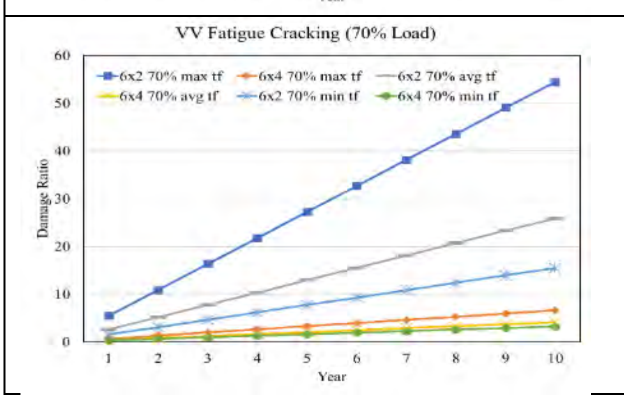
Damage Ratio
Year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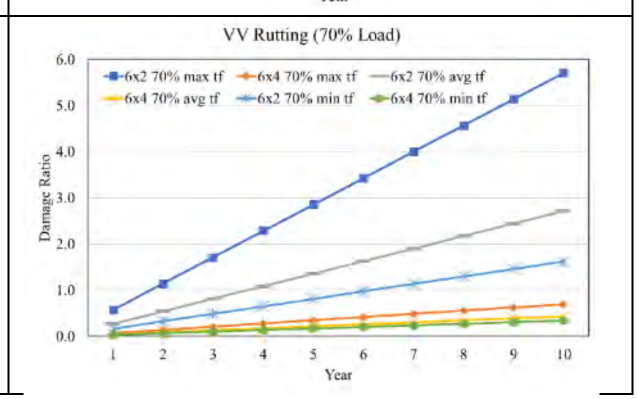
Damage Ratio
Year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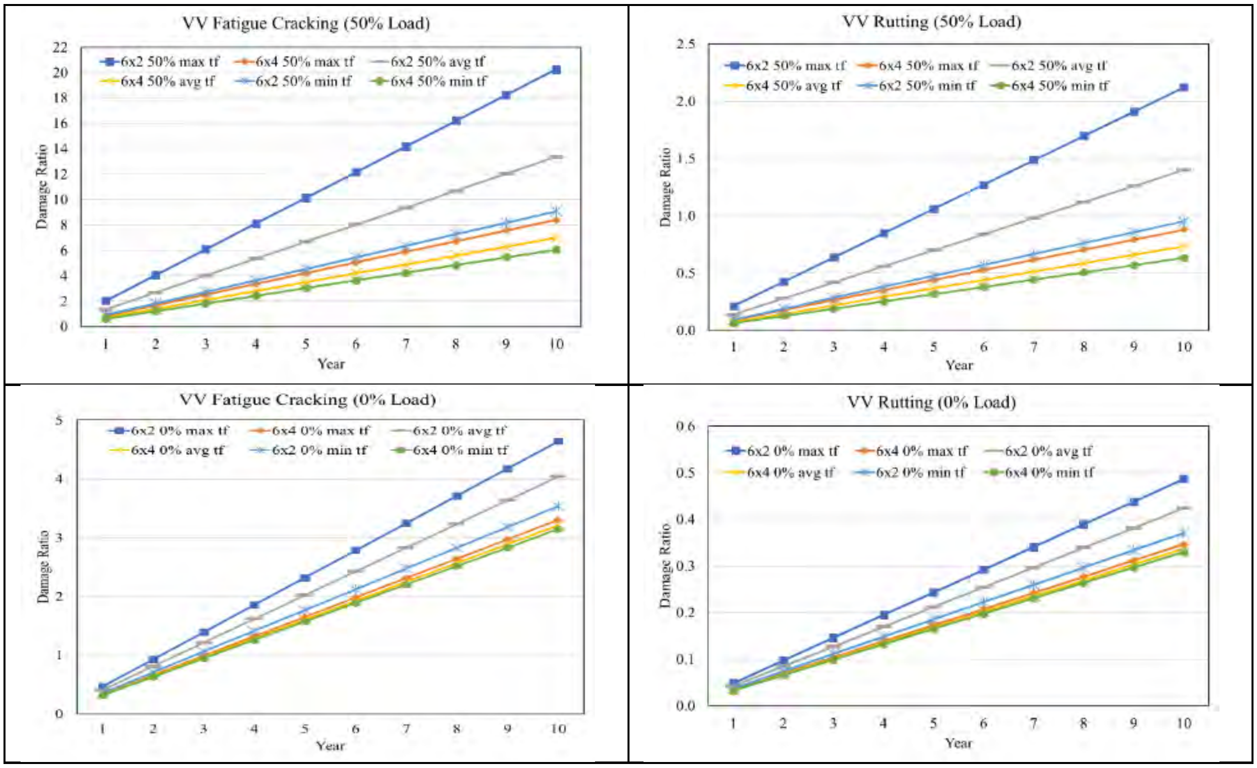
Damage Ratio
Year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Damage Ratio
Year
VV Rutting (50% Load)
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6x4 50% max tf
6x2 50% avg tf
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Damage Ratio
Year
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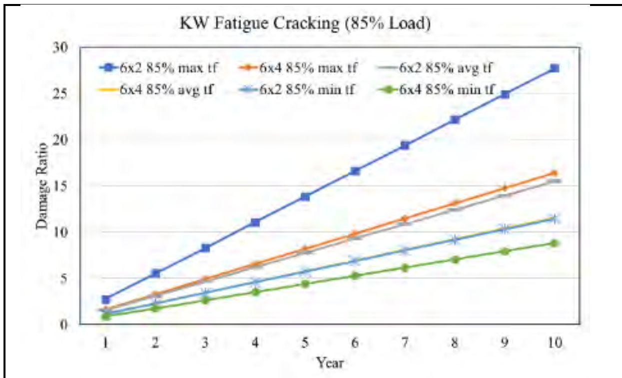
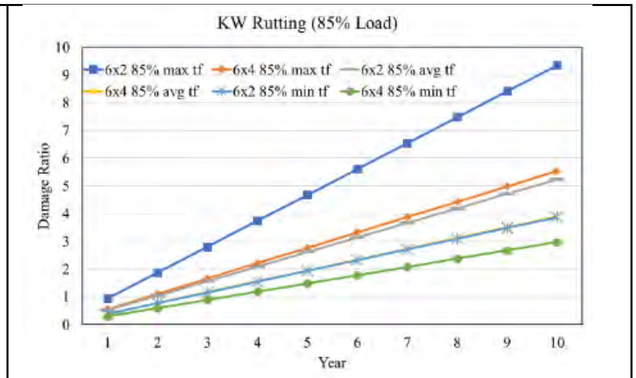
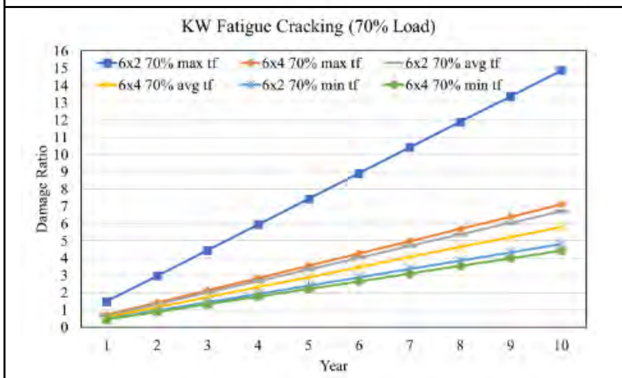
6x4 0% min tf
Damage Ratio
Year
VV Rutting (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year

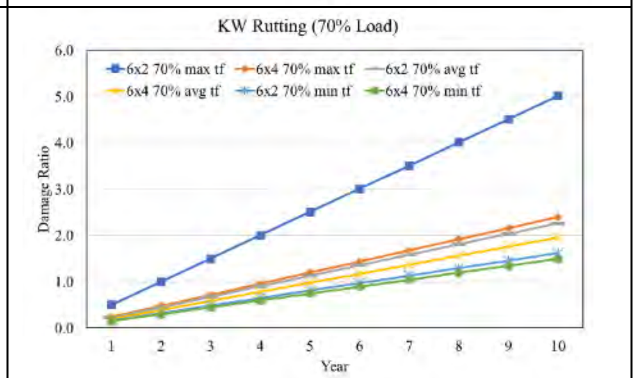
Minor Arterial Road

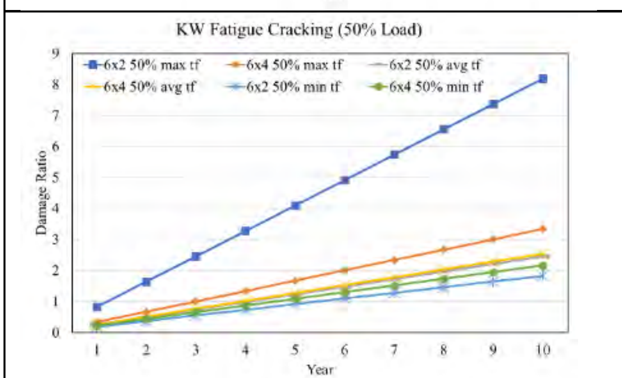
Kenworth (KW)

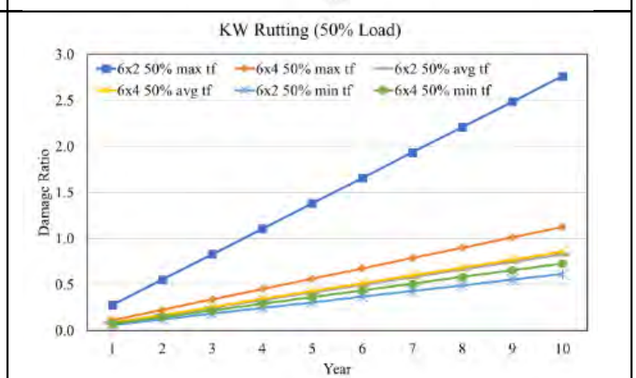


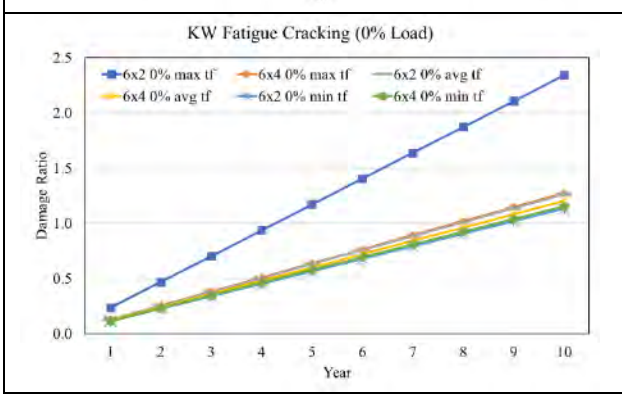


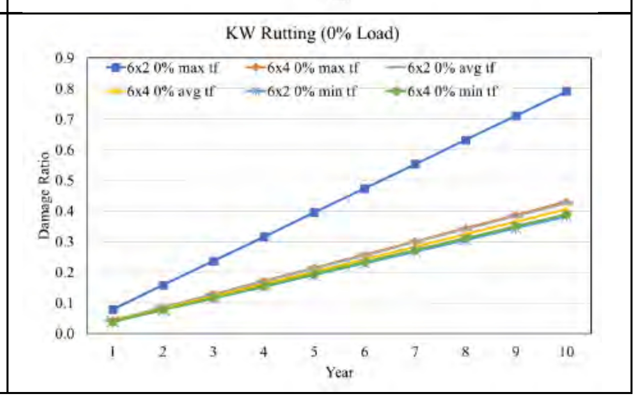




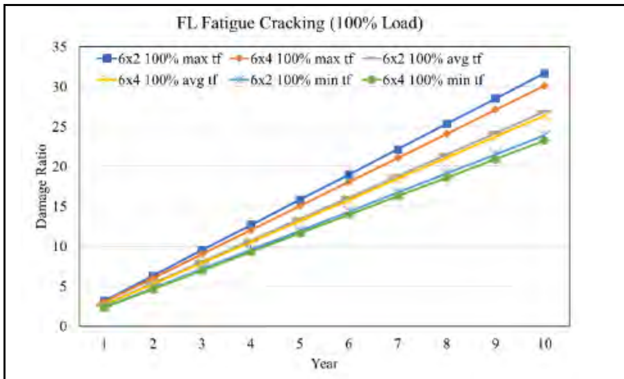


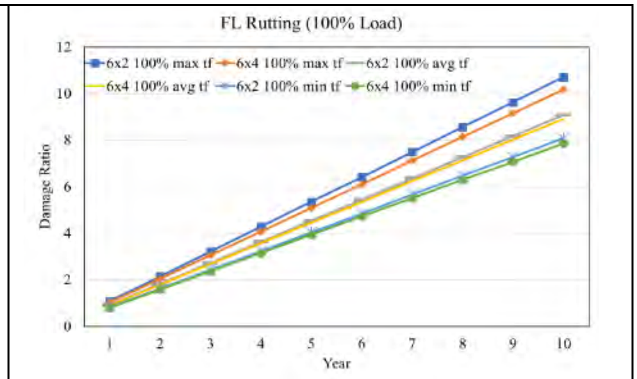


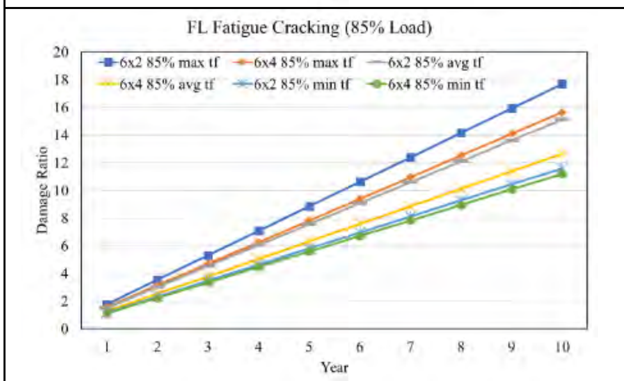


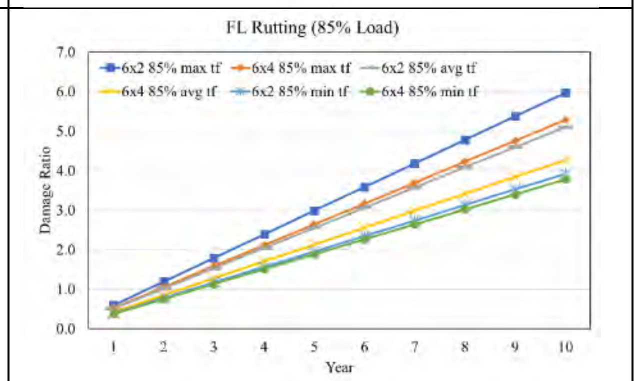


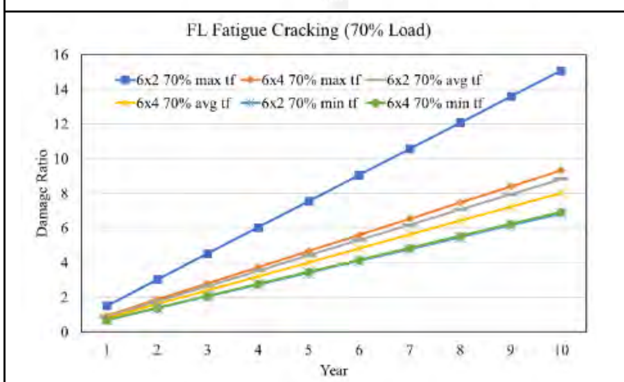
Frieghtliner (FL)

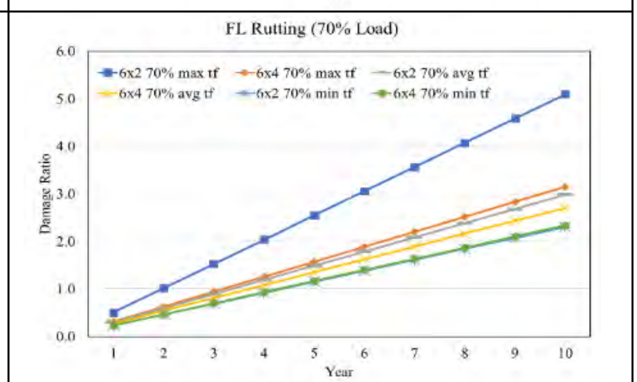


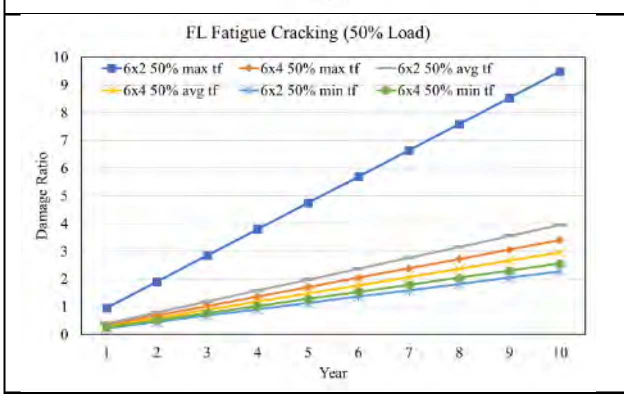


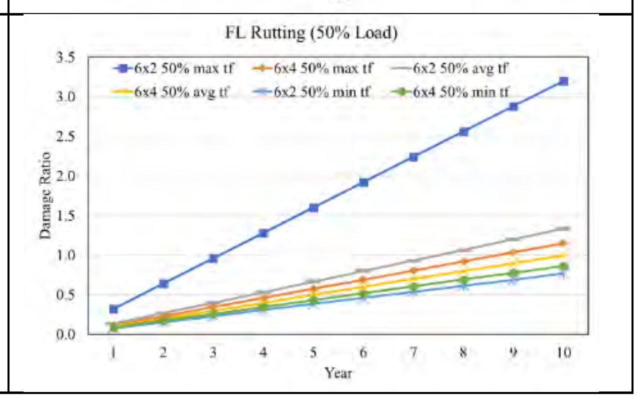


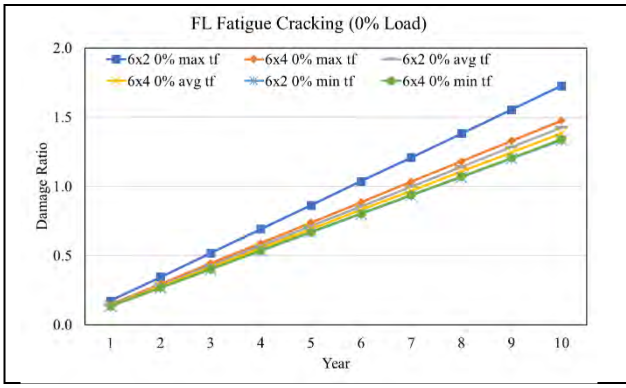


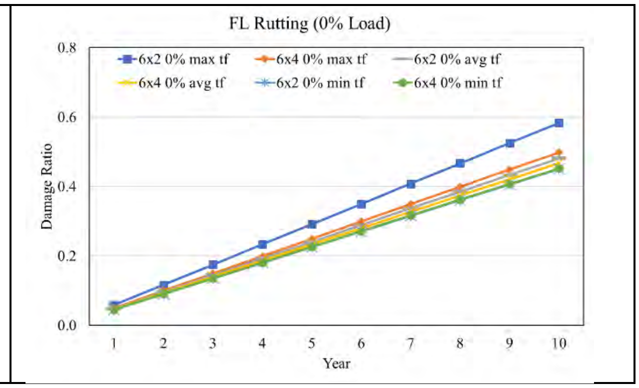




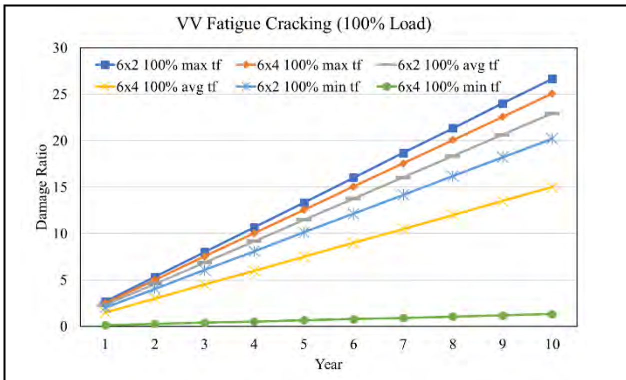


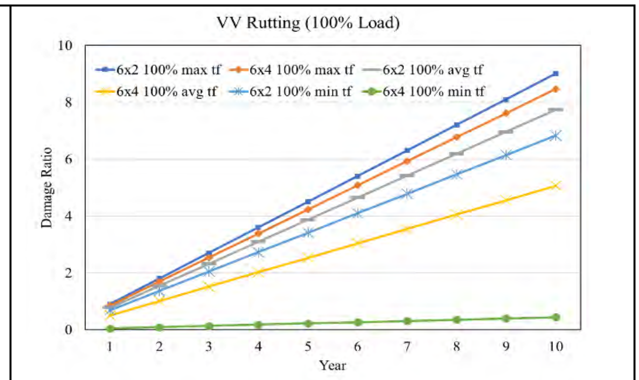


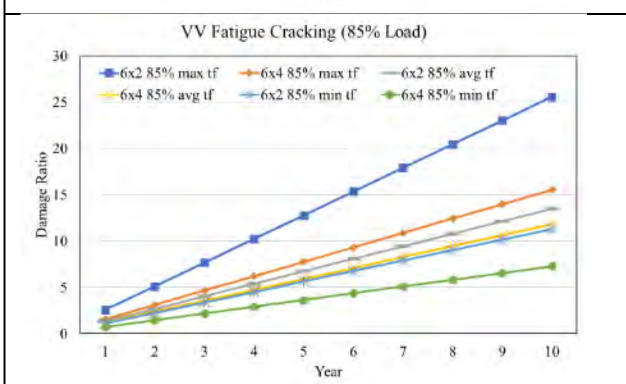

FL Fatigue Cracking (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year

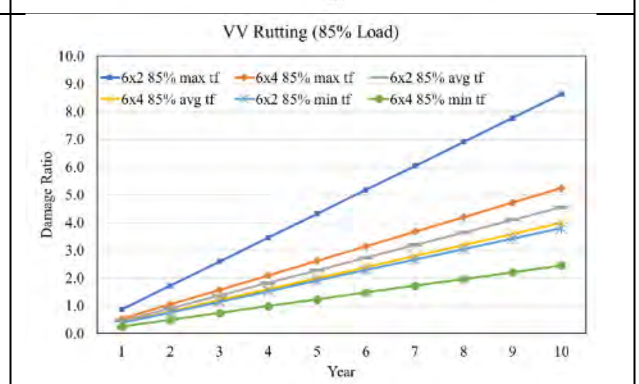

FL Rutting (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year

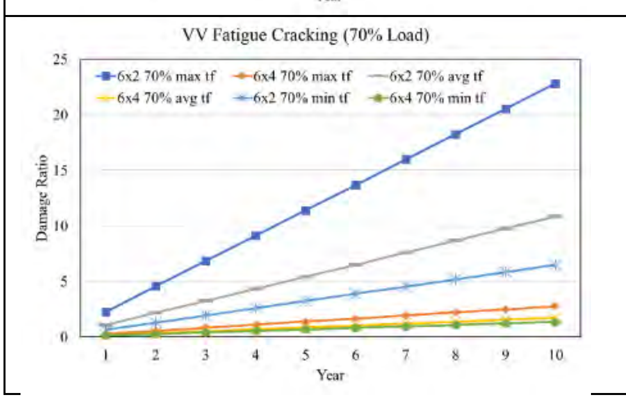
Volvo (VV)

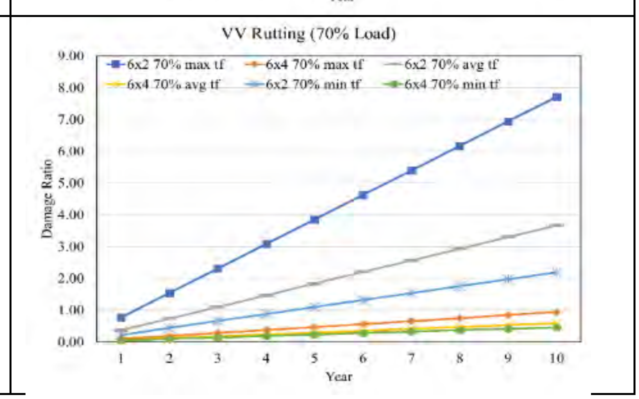

VV Fatigue Cracking (100% Load)
6x2 100% max tf
6x4 100% max tf
6x2 100% avg tf
6x4 100% avg tf
6x2 100% min tf
6x4 100% min tf
Damage Ratio
Year

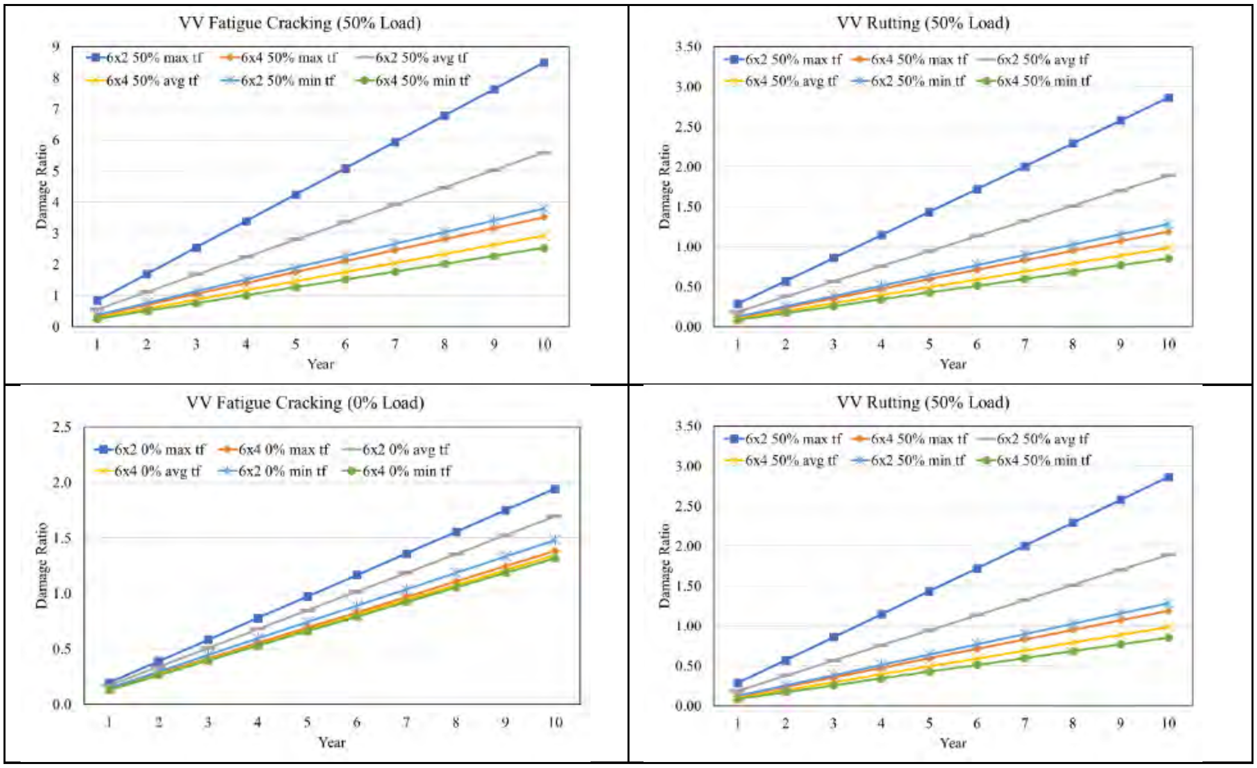

VV Rutting (100% Load)
6x2 100% max tf
6x4 100% max tf
6x2 100% avg tf
6x4 100% avg tf
6x2 100% min tf
6x4 100% min tf
Damage Ratio
Year


VV Fatigue Cracking (85% Load)
6x2 85% max tf
6x4 85% max tf
6x2 85% avg tf
6x4 85% avg tf
6x2 85% min tf
6x4 85% min tf
Damage Ratio
Year


VV Rutting (85% Load)
6x2 85% max tf
6x4 85% max tf
6x2 85% avg tf
6x4 85% avg tf
6x2 85% min tf
6x4 85% min tf
Damage Ratio
Year

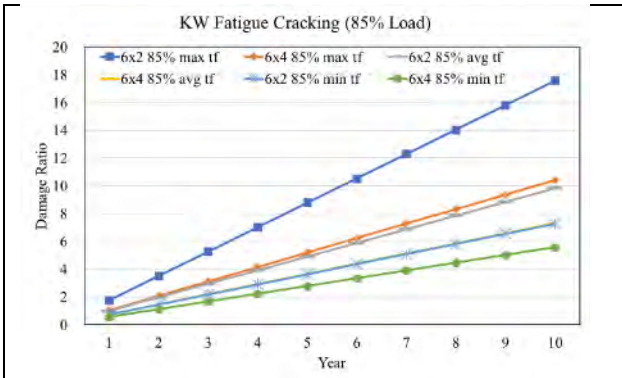

VV Fatigue Cracking (70% Load)
6x2 70% max tf
6x4 70% max tf
6x2 70% avg tf
6x4 70% avg tf
6x2 70% min tf
6x4 70% min tf
Damage Ratio
Year

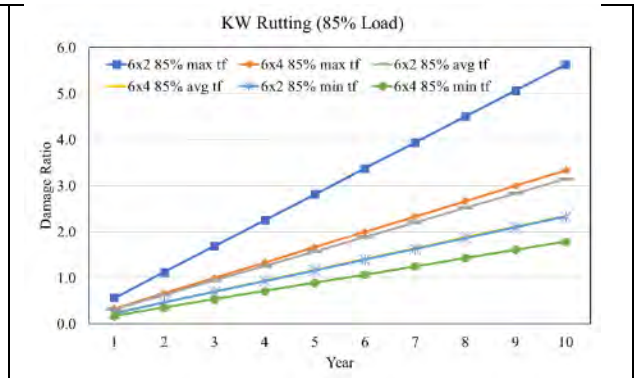

VV Rutting (70% Load)
6x2 70% max tf
6x4 70% max tf
6x2 70% avg tf
6x4 70% avg tf
6x2 70% min tf
6x4 70% min tf
Damage Ratio
Year

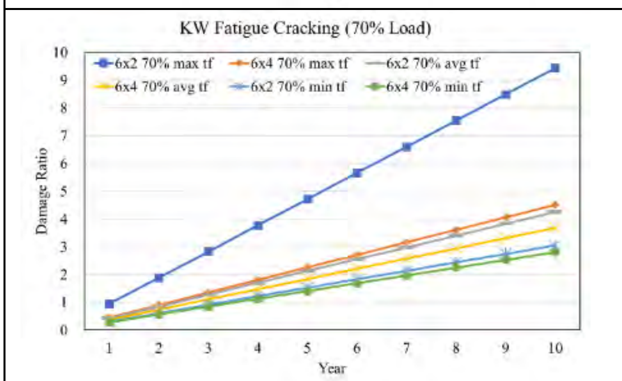

VV Fatigue Cracking (50% Load)
6x2 50% max tf
6x4 50% max tf
6x2 50% avg tf
6x4 50% avg tf
6x2 50% min tf
6x4 50% min tf
Damage Ratio
Year
VV Rutting (50% Load)
6x2 50% max tf
6x4 50% max tf
6x2 50% avg tf
6x4 50% avg tf
6x2 50% min tf
6x4 50% min tf
Damage Ratio
Year
VV Fatigue Cracking (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year
VV Rutting (50% Load)
6x2 50% max tf
6x4 50% max tf
6x2 50% avg tf
6x4 50% avg tf
6x2 50% min tf
6x4 50% min tf
Damage Ratio
Year

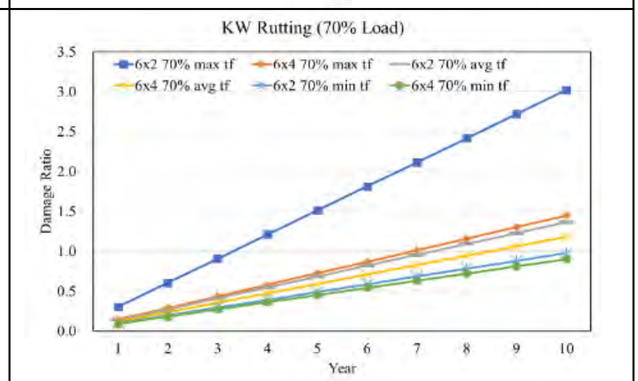
Collector

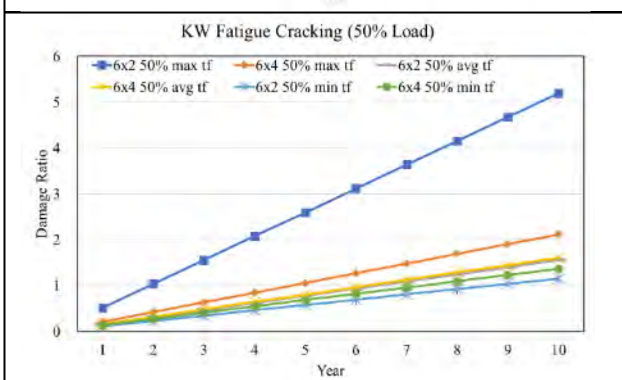
Kenworth (KW)

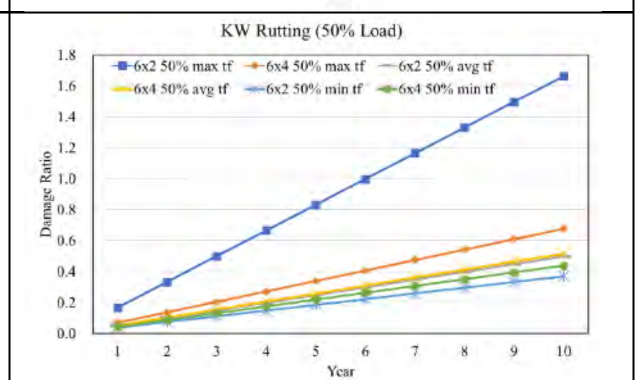


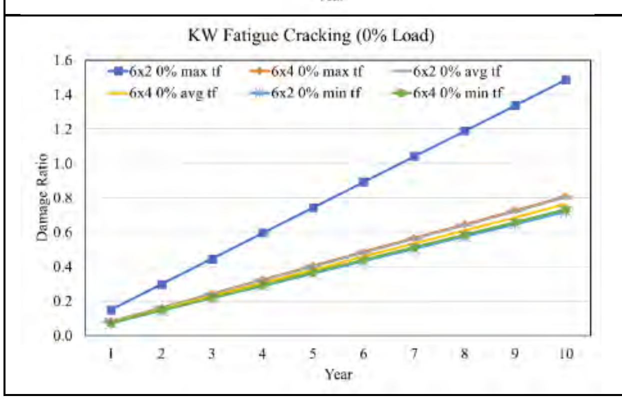


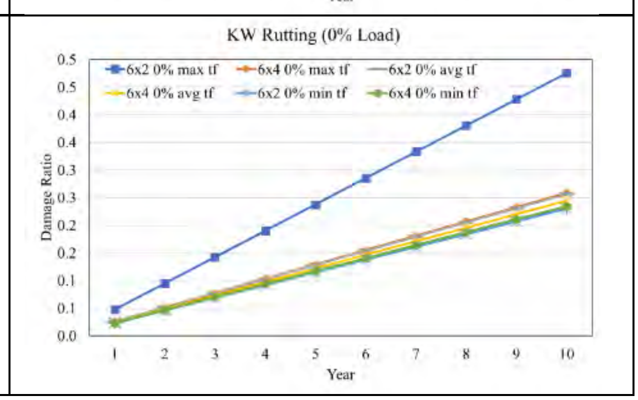




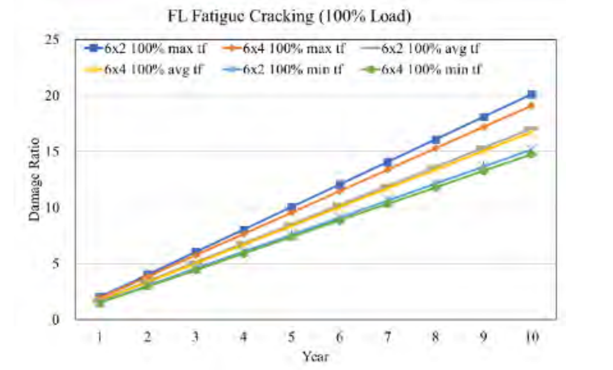


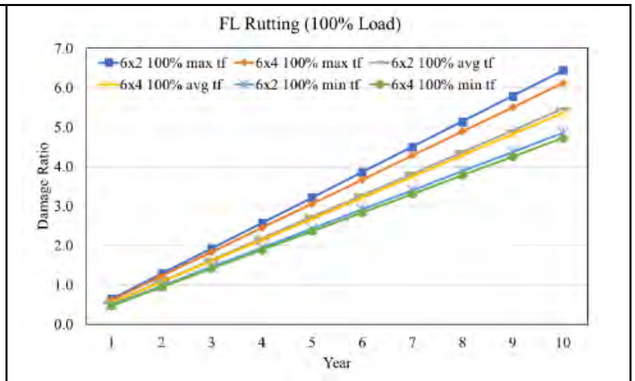


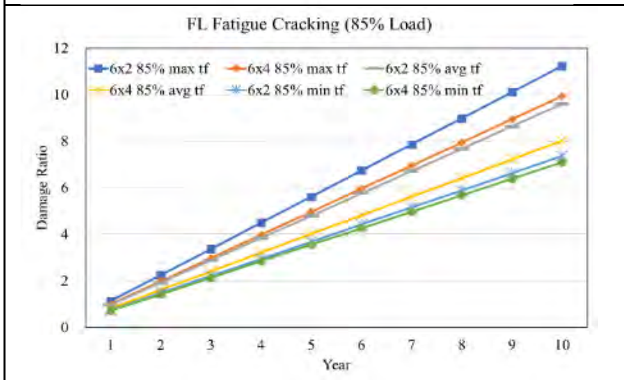


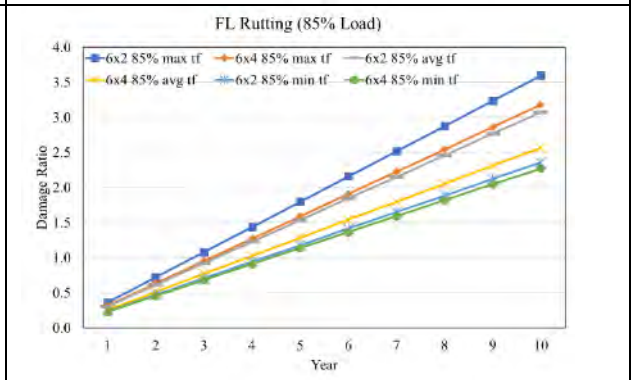


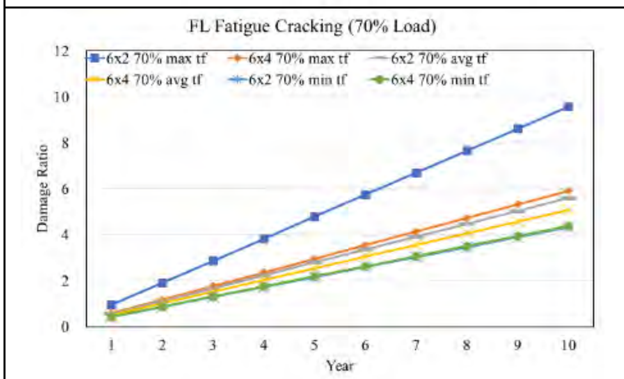
Frieghtliner (FL)

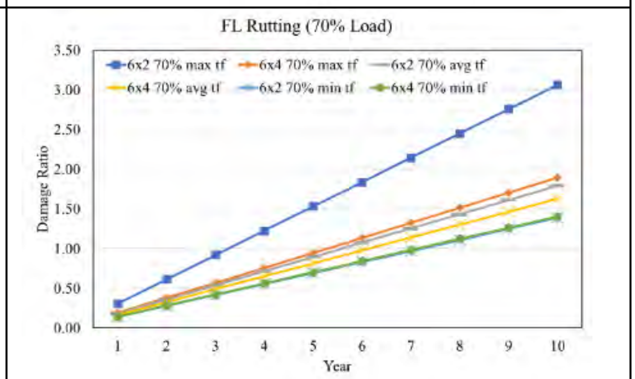


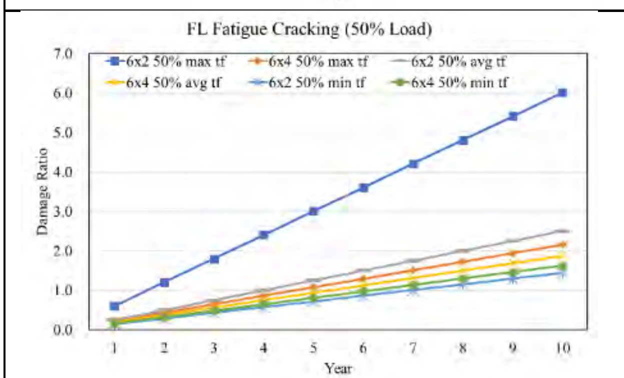


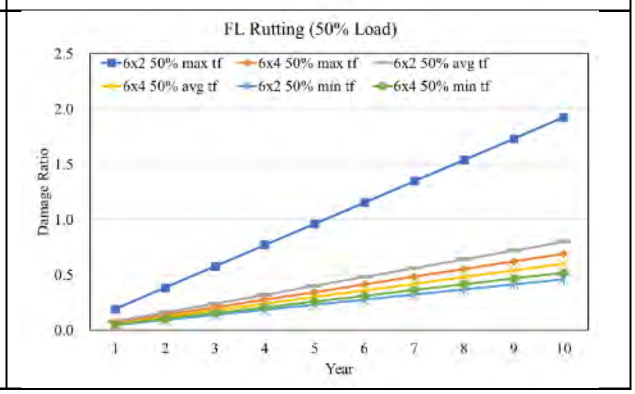


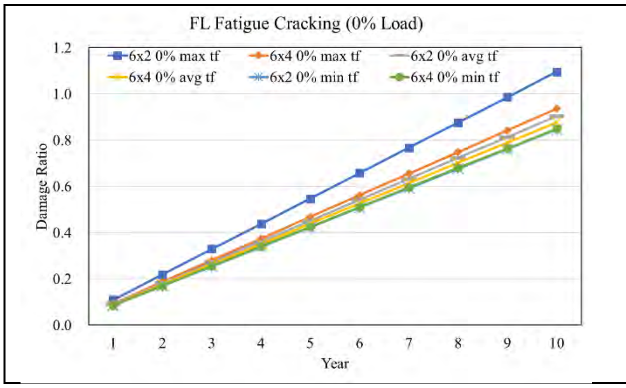


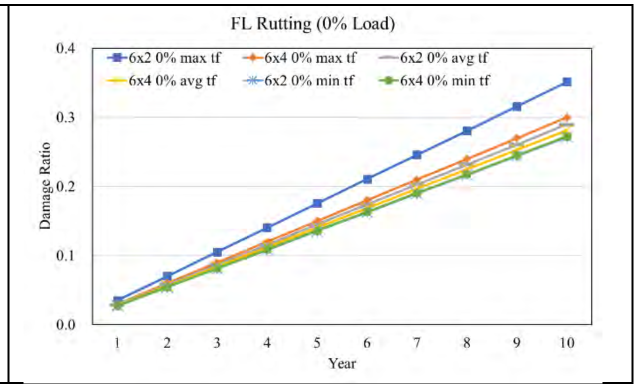




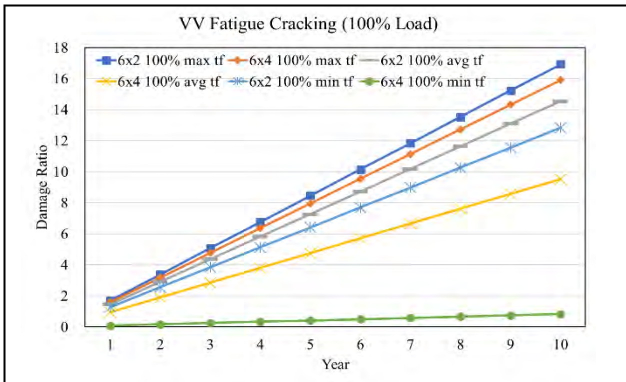


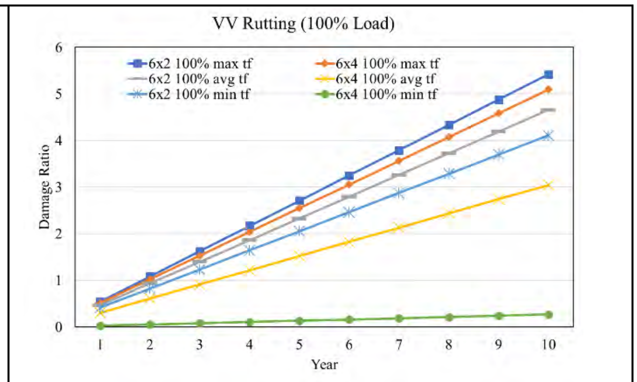


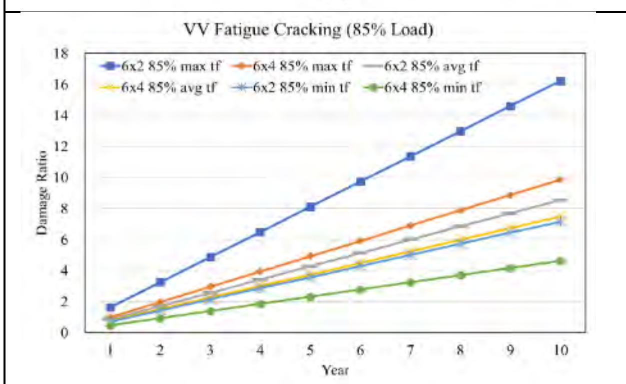

FL Fatigue Cracking (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year

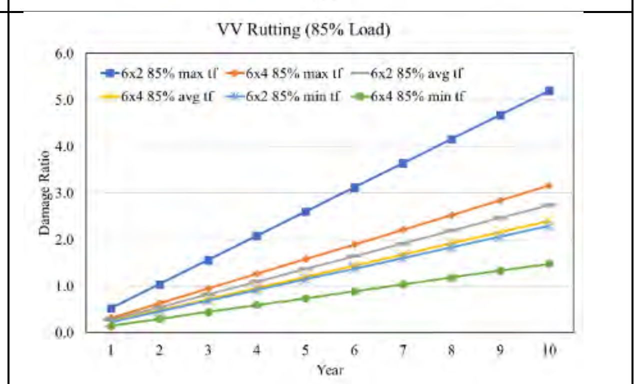

FL Rutting (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year

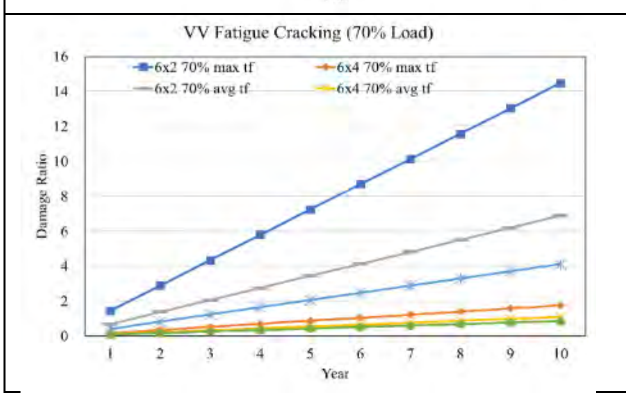
Volvo (VV)

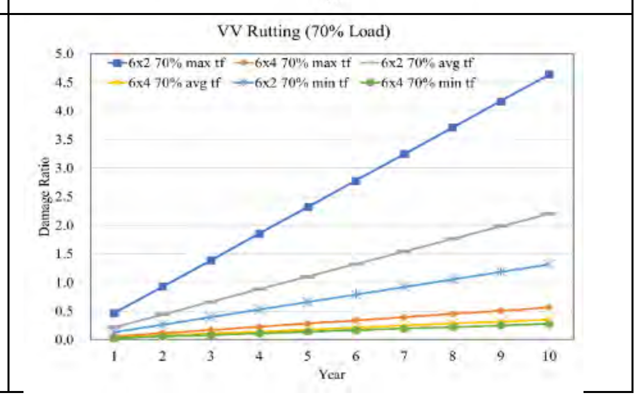

VV Fatigue Cracking (100% Load)
6x2 100% max tf
6x4 100% max tf
6x2 100% avg tf
6x4 100% avg tf
6x2 100% min tf
6x4 100% min tf
Damage Ratio
Year

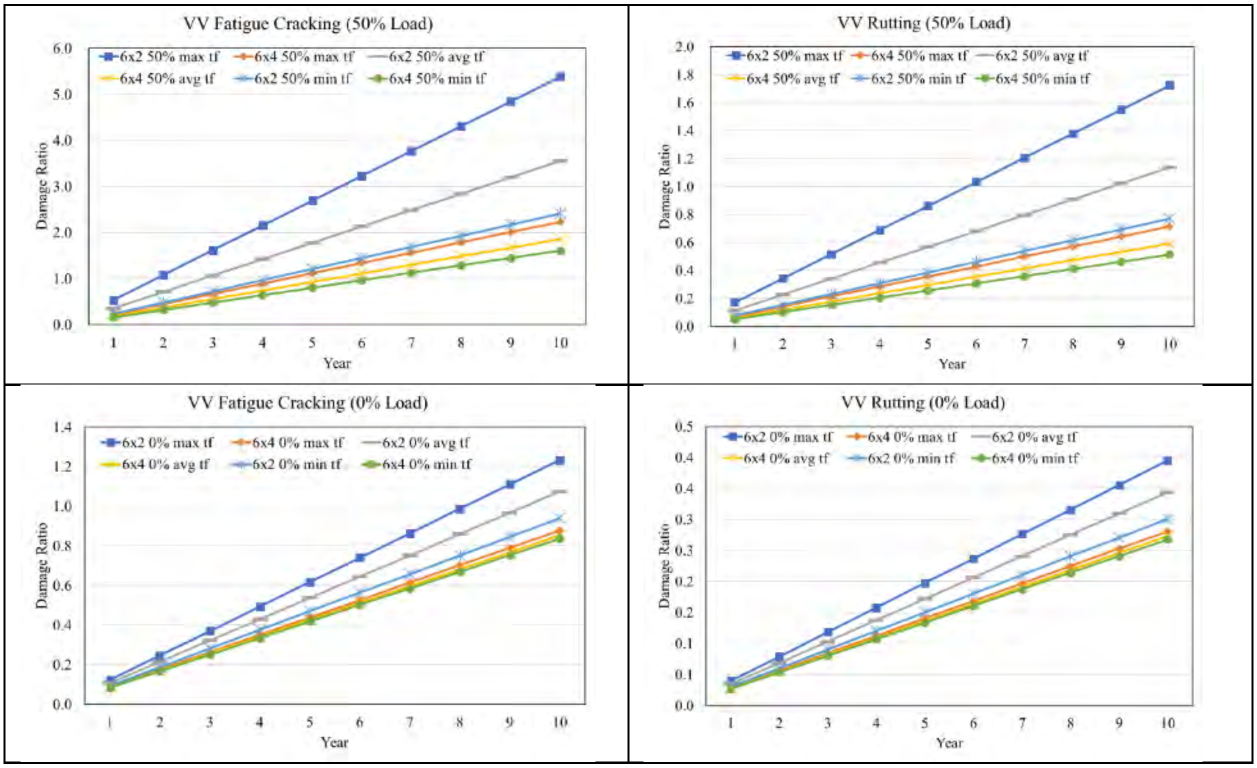

VV Rutting (100% Load)
6x2 100% max tf
6x4 100% max tf
6x2 100% avg tf
6x4 100% avg tf
6x2 100% min tf
6x4 100% min tf
Damage Ratio
Year


VV Fatigue Cracking (85% Load)
6x2 85% max tf
6x4 85% max tf
6x2 85% avg tf
6x4 85% avg tf
6x2 85% min tf
6x4 85% min tf
Damage Ratio
Year


VV Rutting (85% Load)
6x2 85% max tf
6x4 85% max tf
6x2 85% avg tf
6x4 85% avg tf
6x2 85% min tf
6x4 85% min tf
Damage Ratio
Year

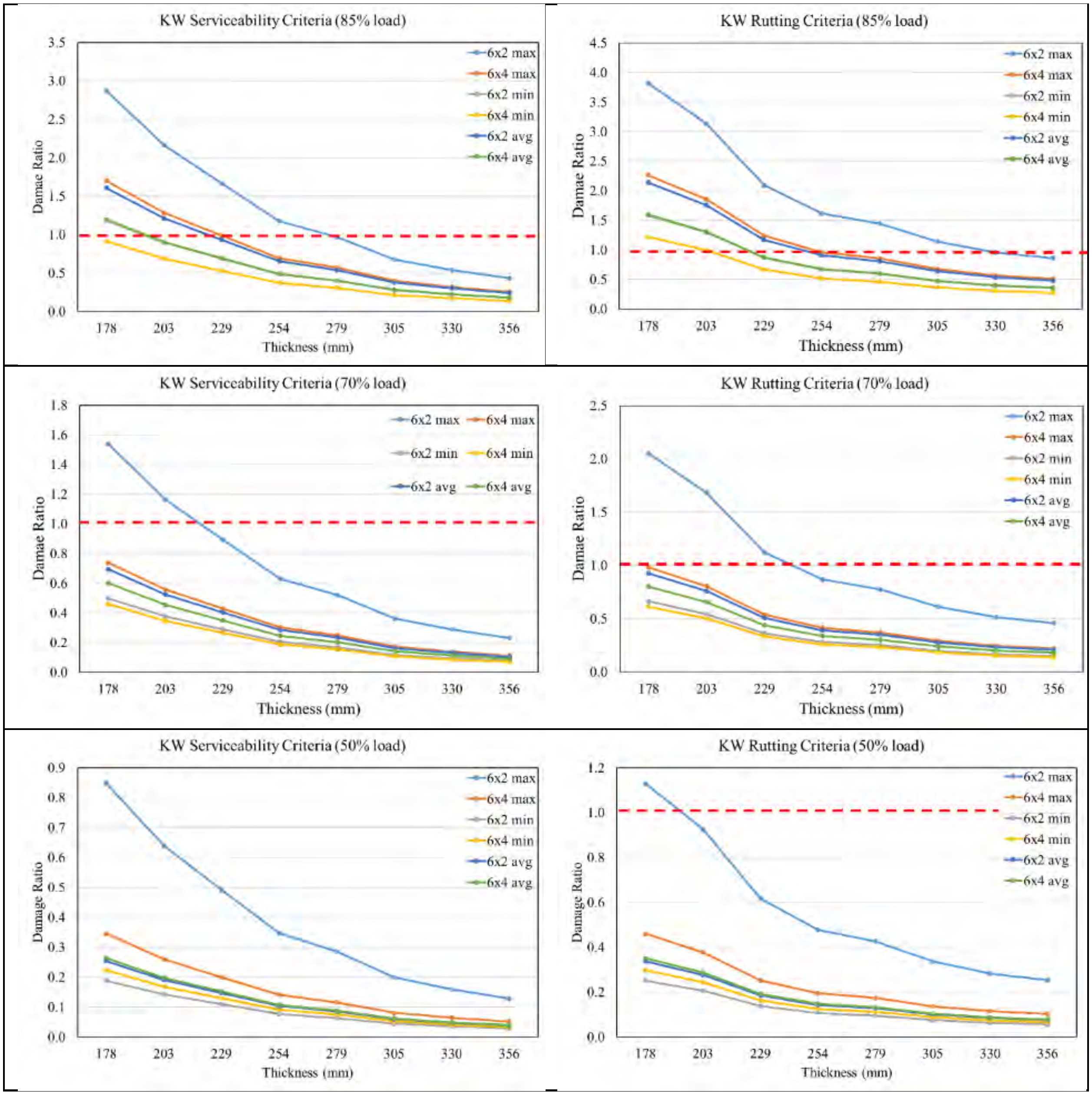

VV Fatigue Cracking (70% Load)
6x2 70% max tf
6x4 70% max tf
6x2 70% avg tf
6x4 70% avg tf
Damage Ratio
Year

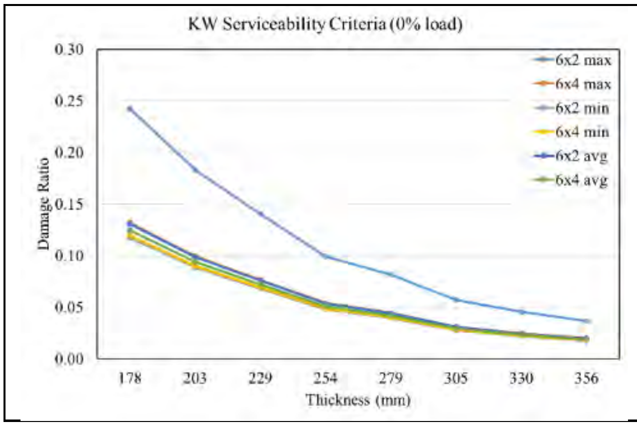

VV Rutting (70% Load)
6x2 70% max tf
6x4 70% max tf
6x2 70% avg tf
6x4 70% avg tf
6x2 70% min tf
6x4 70% min tf
Damage Ratio
Year

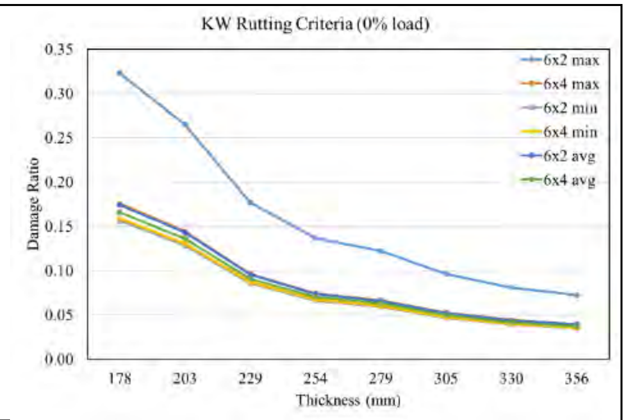

VV Fatigue Cracking (50% Load)
6x2 50% max tf
6x4 50% max tf
6x2 50% avg tf
6x4 50% avg tf
6x2 50% min tf
6x4 50% min tf
Damage Ratio
Year
VV Rutting (50% Load)
6x2 50% max tf
6x4 50% max tf
6x2 50% avg tf
6x4 50% avg tf
6x2 50% min tf
6x4 50% min tf
Damage Ratio
Year
VV Fatigue Cracking (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year
VV Rutting (0% Load)
6x2 0% max tf
6x4 0% max tf
6x2 0% avg tf
6x4 0% avg tf
6x2 0% min tf
6x4 0% min tf
Damage Ratio
Year

Gravel Road

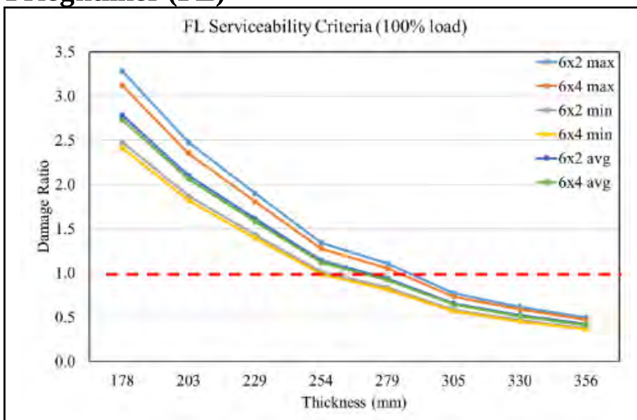
Kenworth (KW)

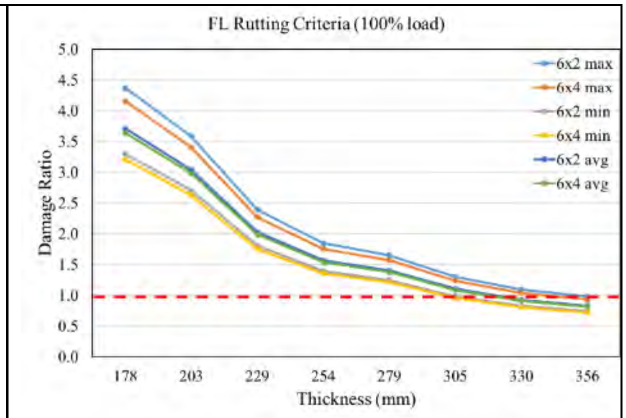


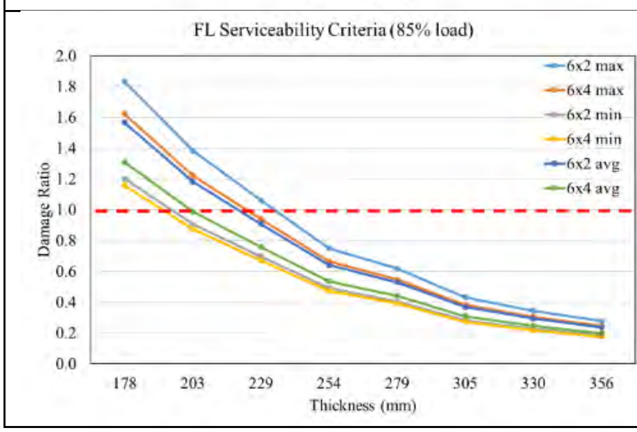


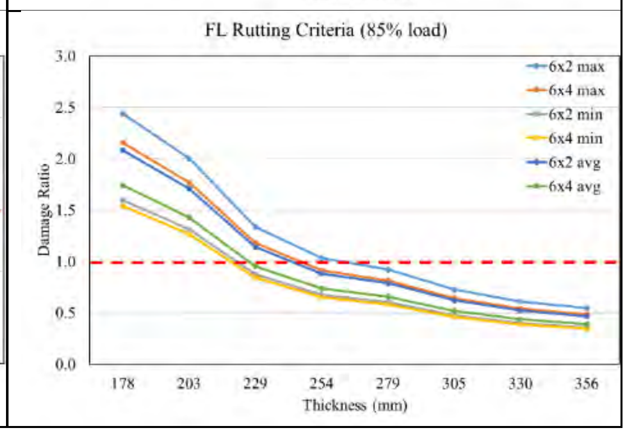


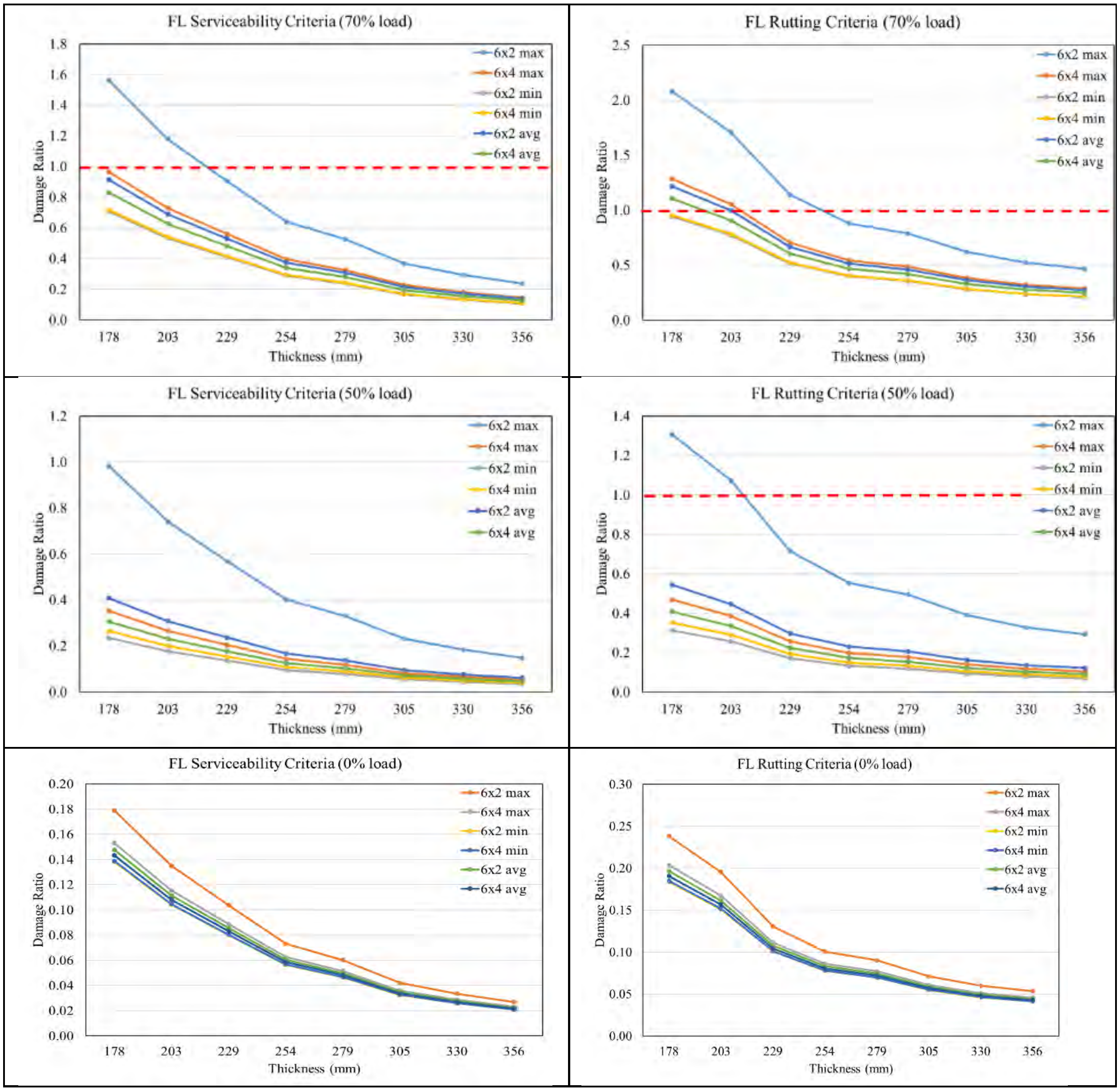
Frieghtliner (FL)



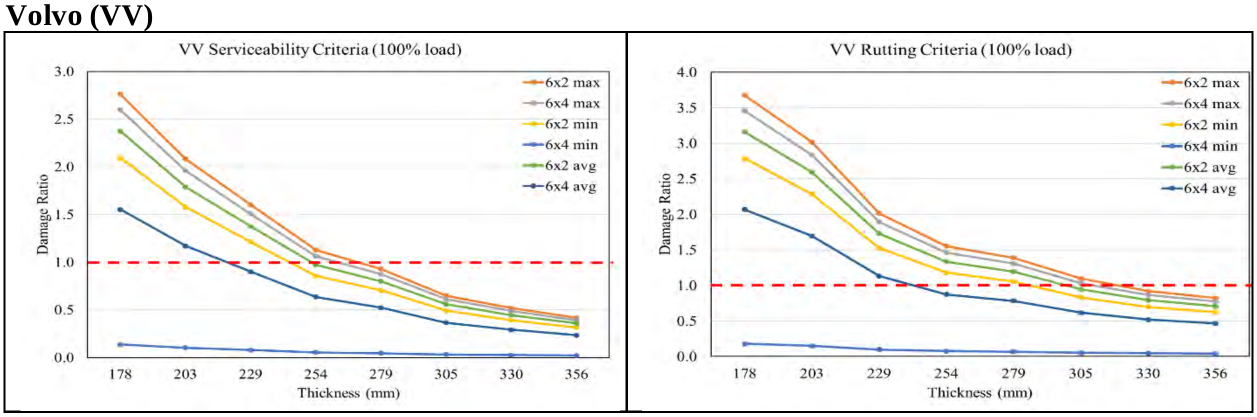


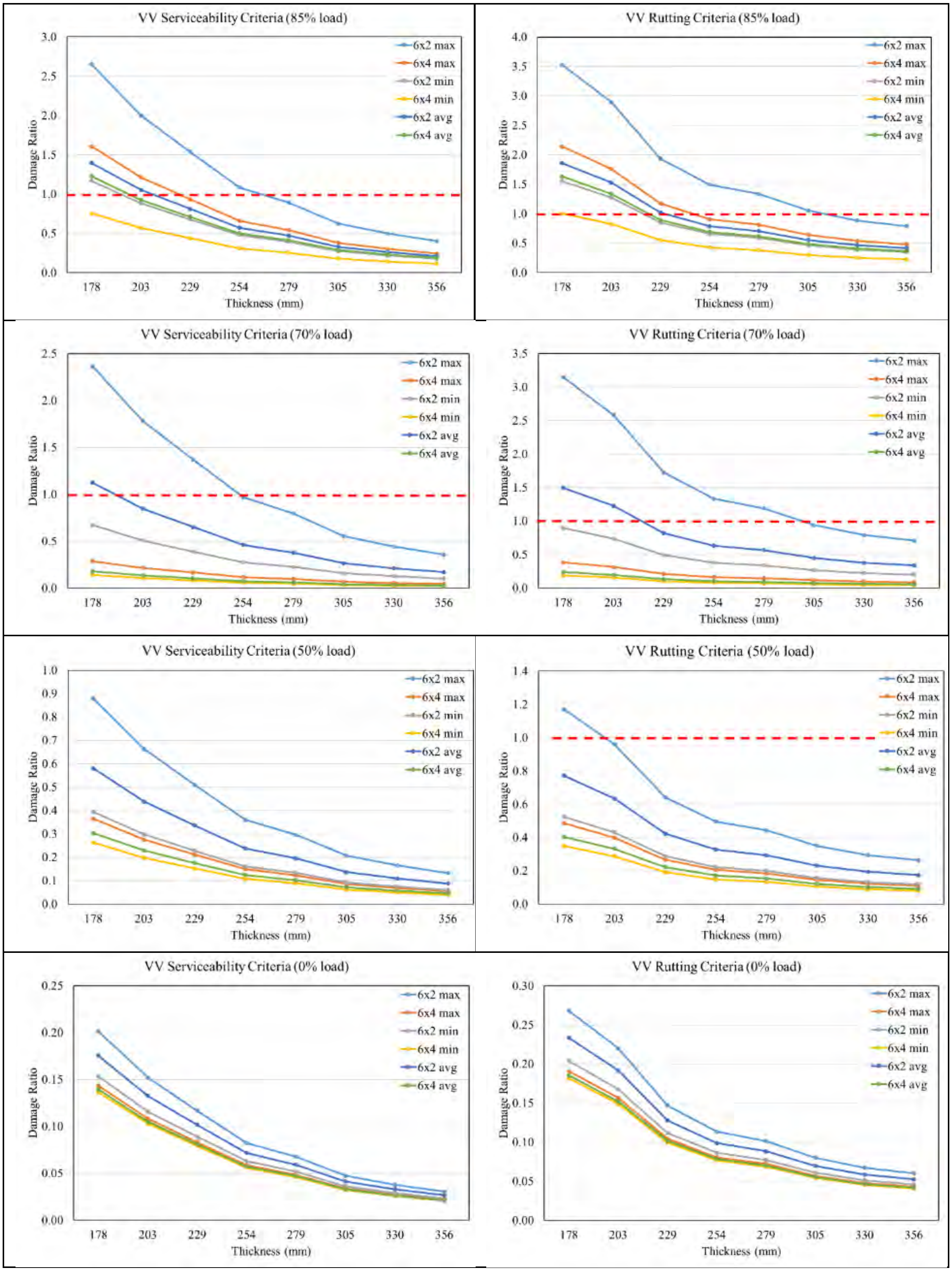





FL Serviceability Criteria (70% load)
FL Rutting Criteria (70% load)
FL Serviceability Criteria (50% load)
FL Rutting Criteria (50% load)
FL Serviceability Criteria (0% load)
FL Rutting Criteria (0% load)
Damage Ratio
Thickness (mm)
6x2 max
6x4 max
6x2 min
6x4 min
6x2 avg
6x4 avg
178
203
229
254
279
305
330
356

Volvo (VV)


VV Serviceability Criteria (100% load)
VV Rutting Criteria (100% load)
Damage Ratio
Thickness (mm)
6x2 max
6x4 max
6x2 min
6x4 min
6x2 avg
6x4 avg
178
203
229
254
279
305
330
356

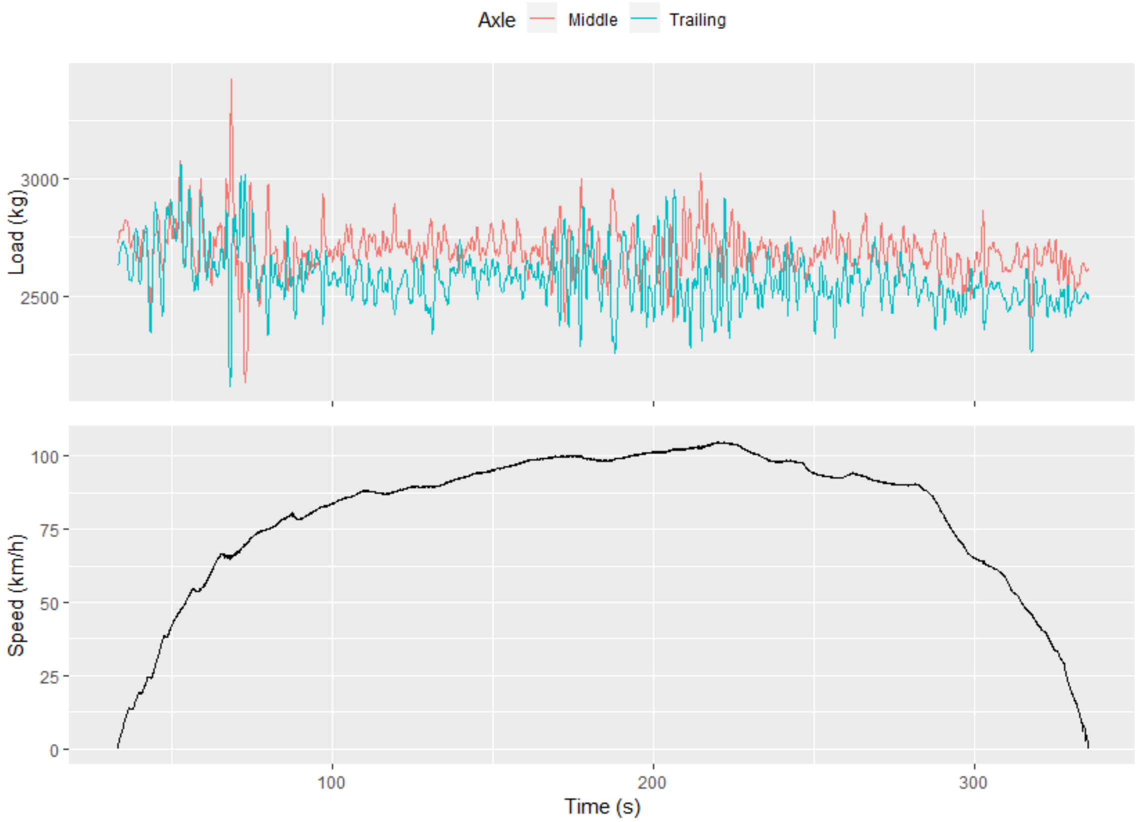

VV Serviceability Criteria (85% load)
VV Rutting Criteria (85% load)
VV Serviceability Criteria (70% load)
VV Rutting Criteria (70% load)
VV Serviceability Criteria (50% load)
VV Rutting Criteria (50% load)
VV Serviceability Criteria (0% load)
VV Rutting Criteria (0% load)
Damage Ratio
Thickness (mm)
178
203
229
254
279
305
330
356
6x2 max
6x4 max
6x2 min
6x4 min
6x2 avg
6x4 avg

Appendix C

Dynamic Axle Load Test Results

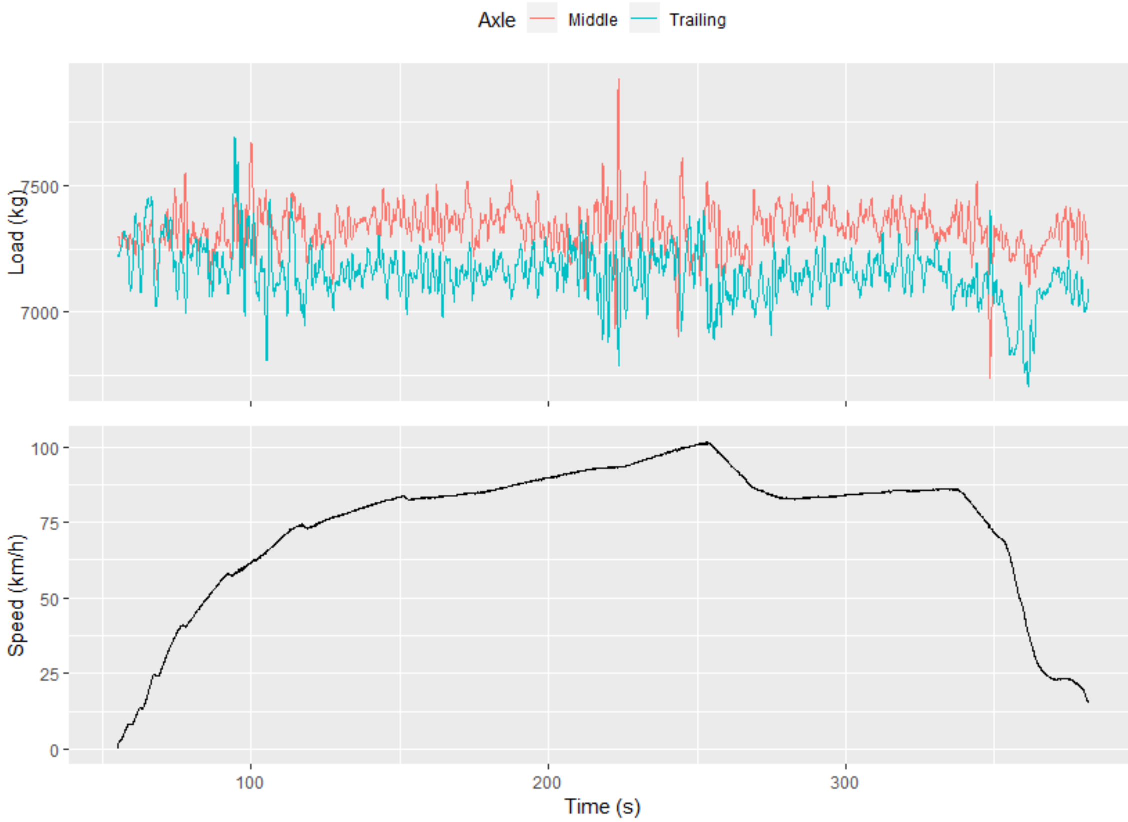
Freightliner

Freightliner 6X4 on Hot Lap at 0% Load

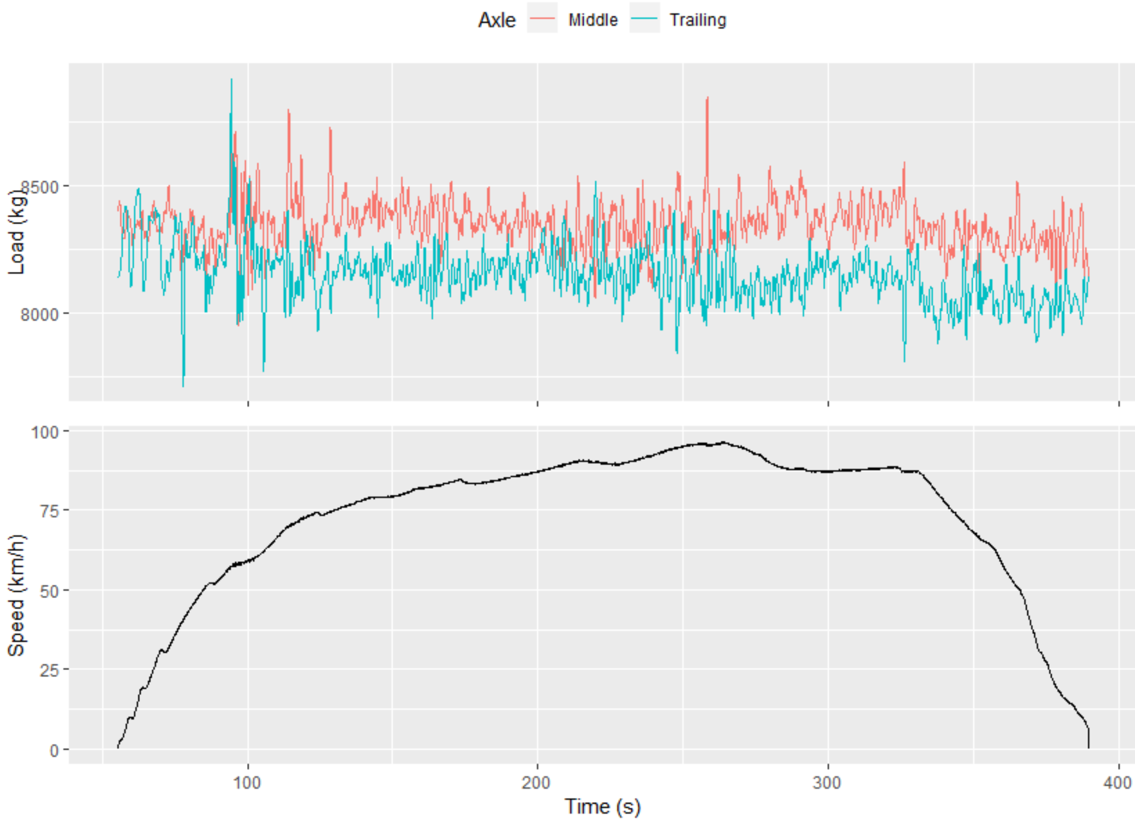


Freightliner 6X4 on Hot Lap at 50% Load

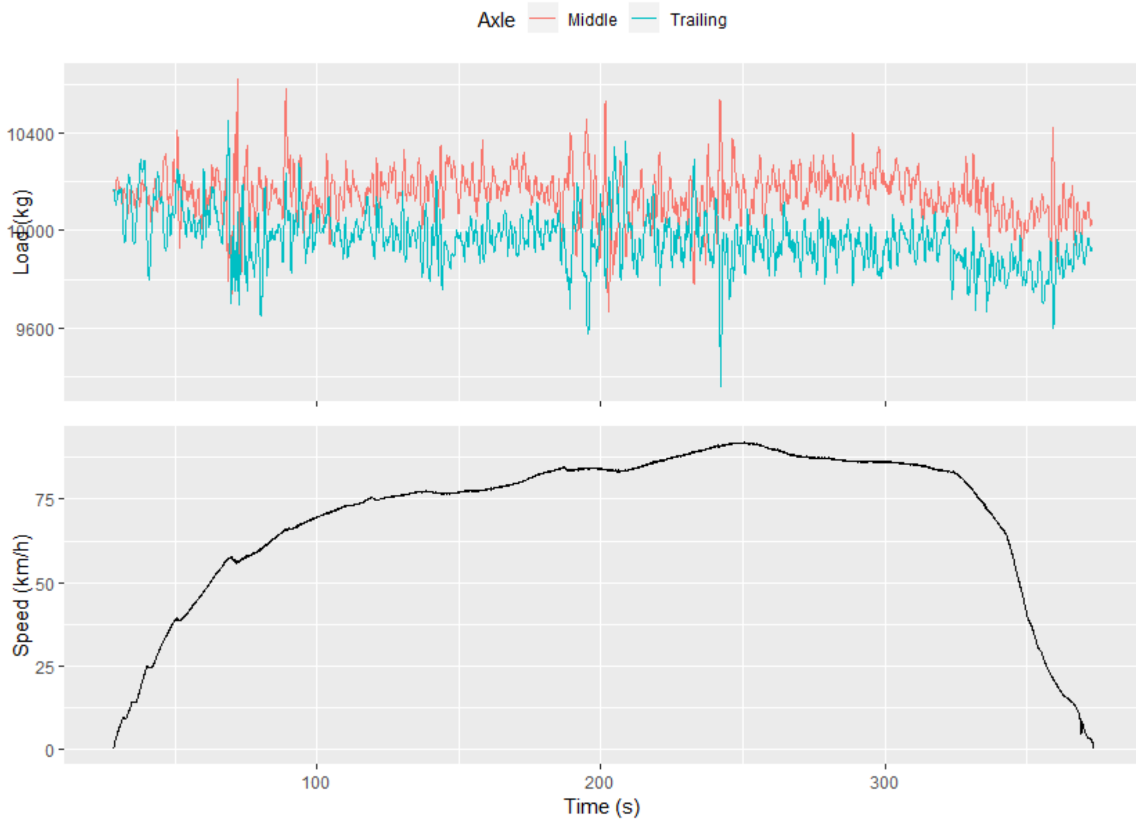
Freightliner 6X4 on Hot Lap at 70% Load



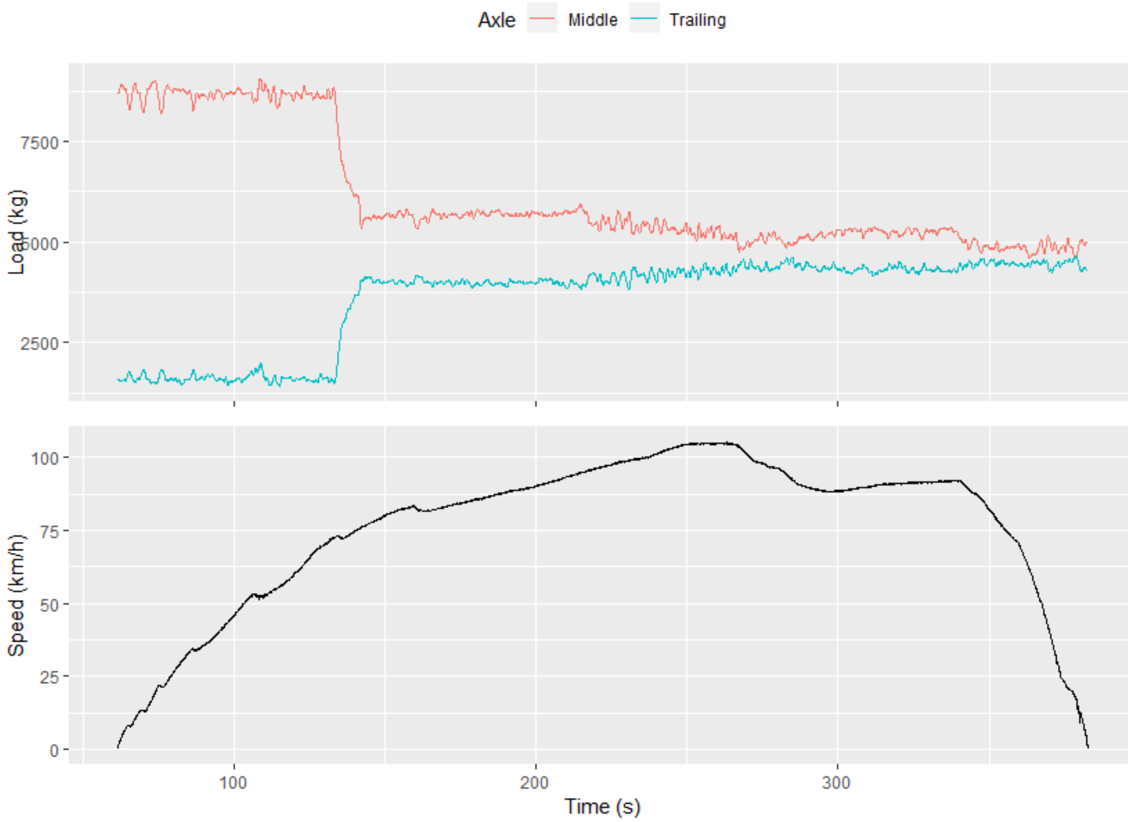
Freightliner 6X4 on Hot Lap at 85% Load



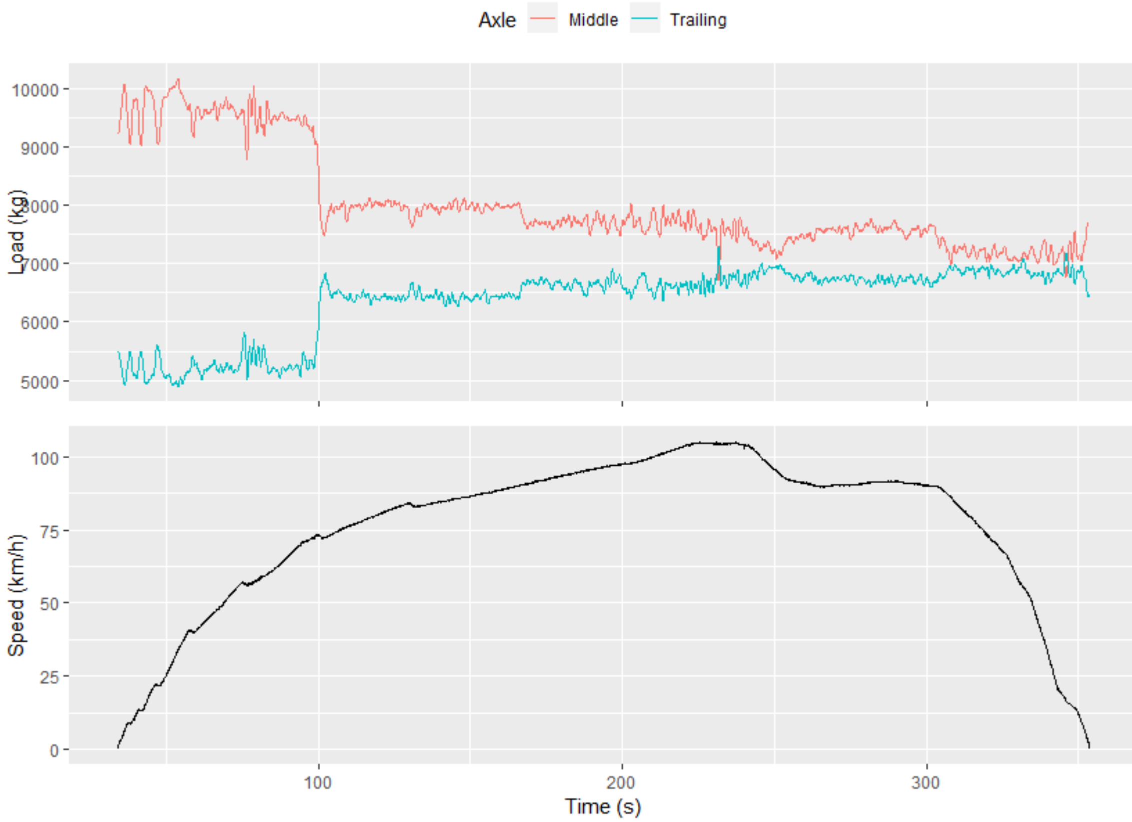
Freightliner 6X4 on Hot Lap at 100% Load



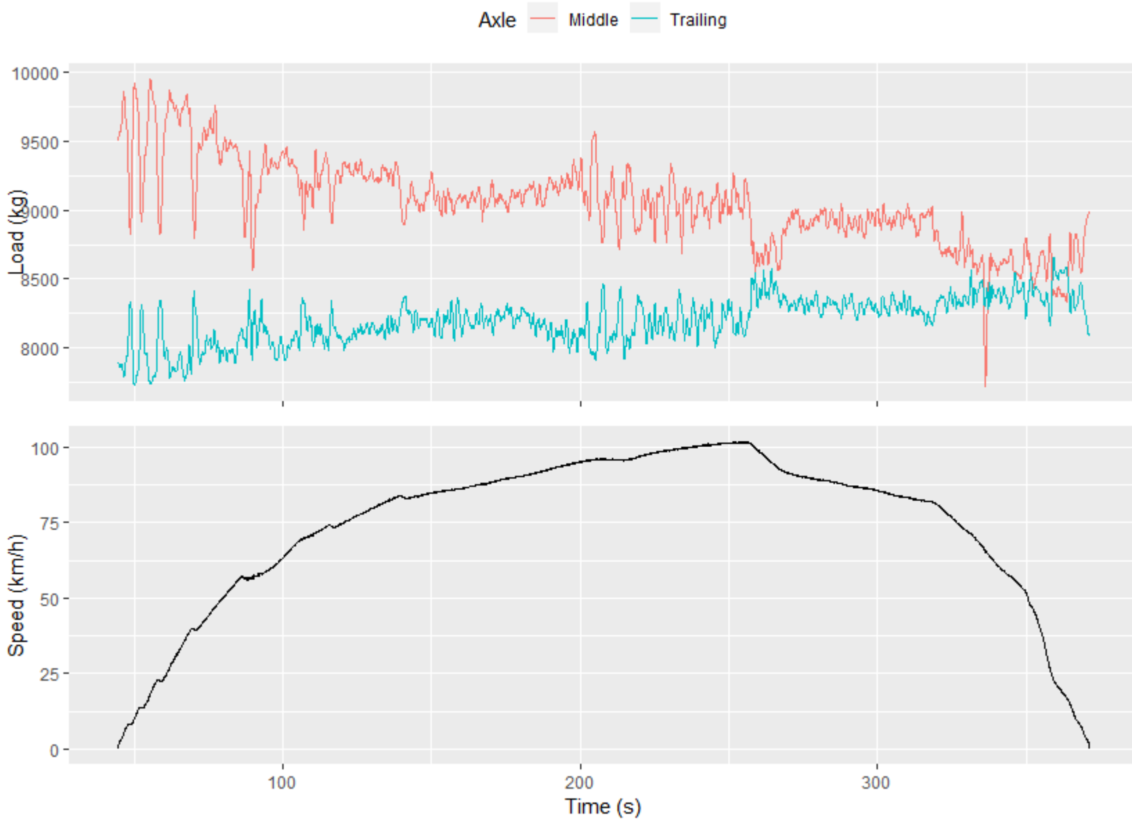
Freightliner 6X2 on Hot Lap at 50% Load



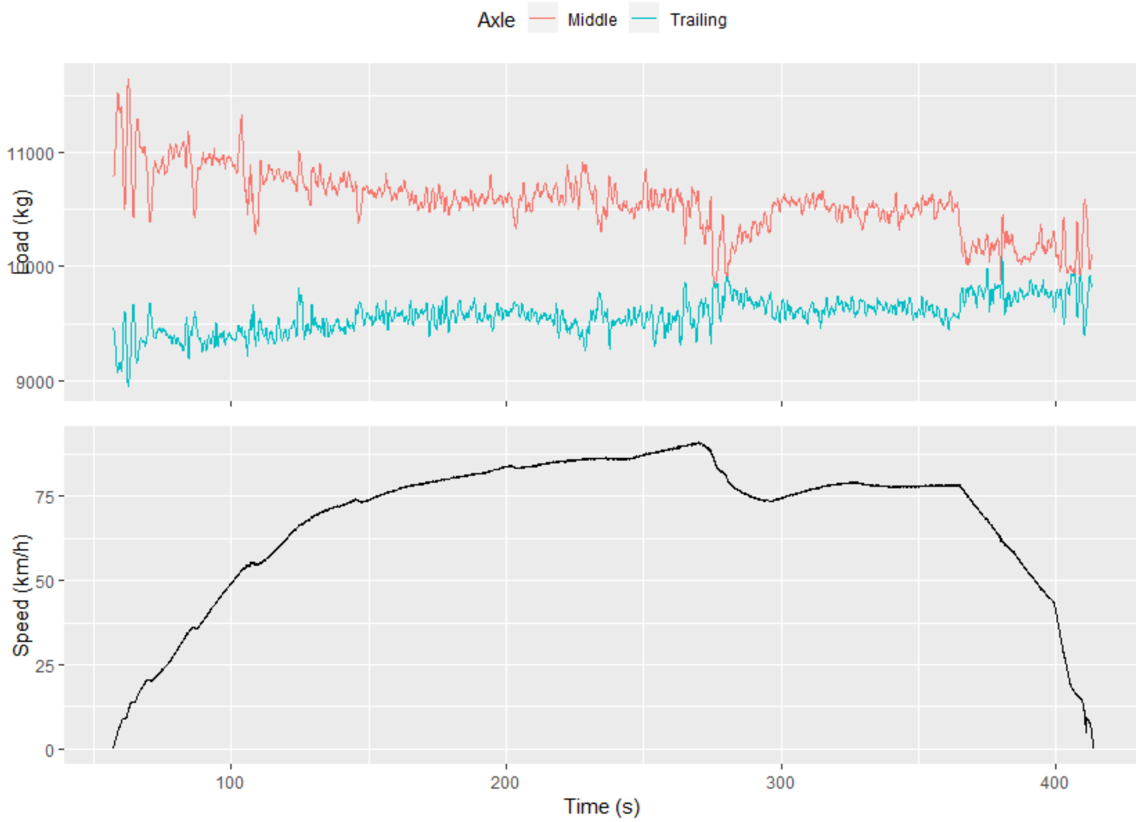
Freightliner 6X2 on Hot Lap at 70% Load



Freightliner 6X2 on Hot Lap at 85% Load



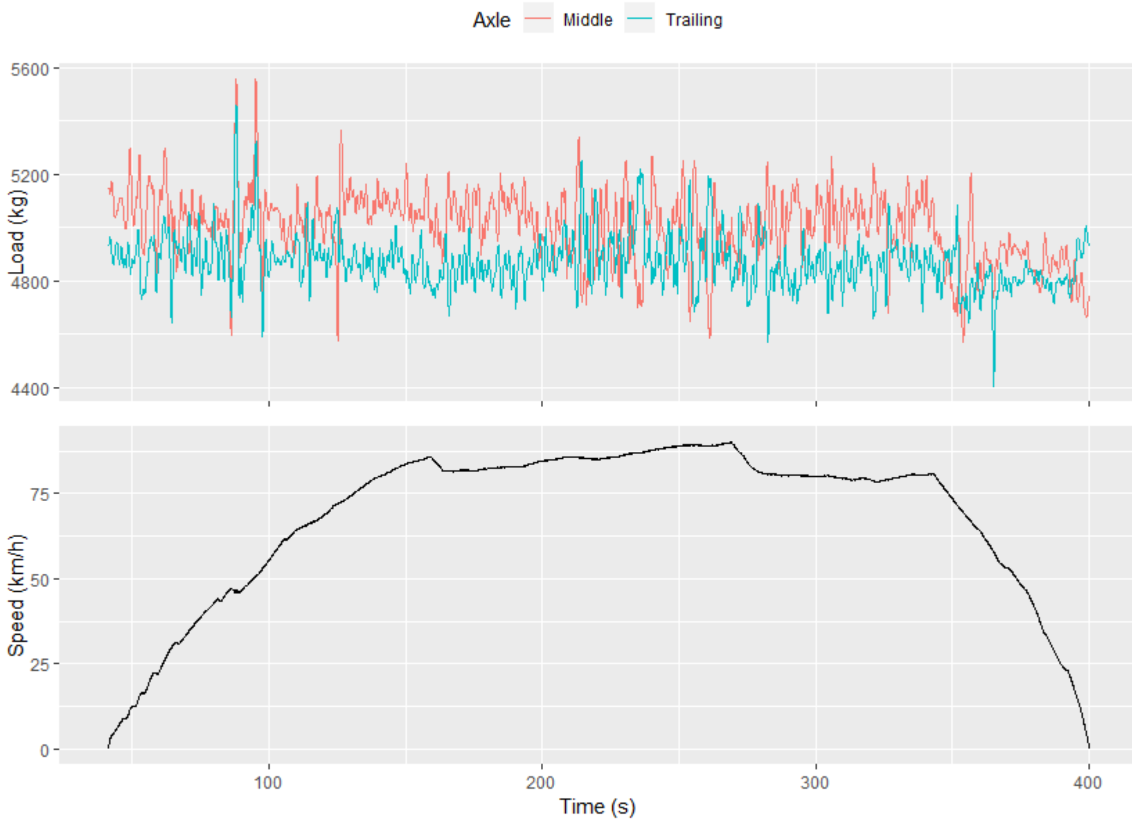
Freightliner 6X2 on Hot Lap at 100% Load



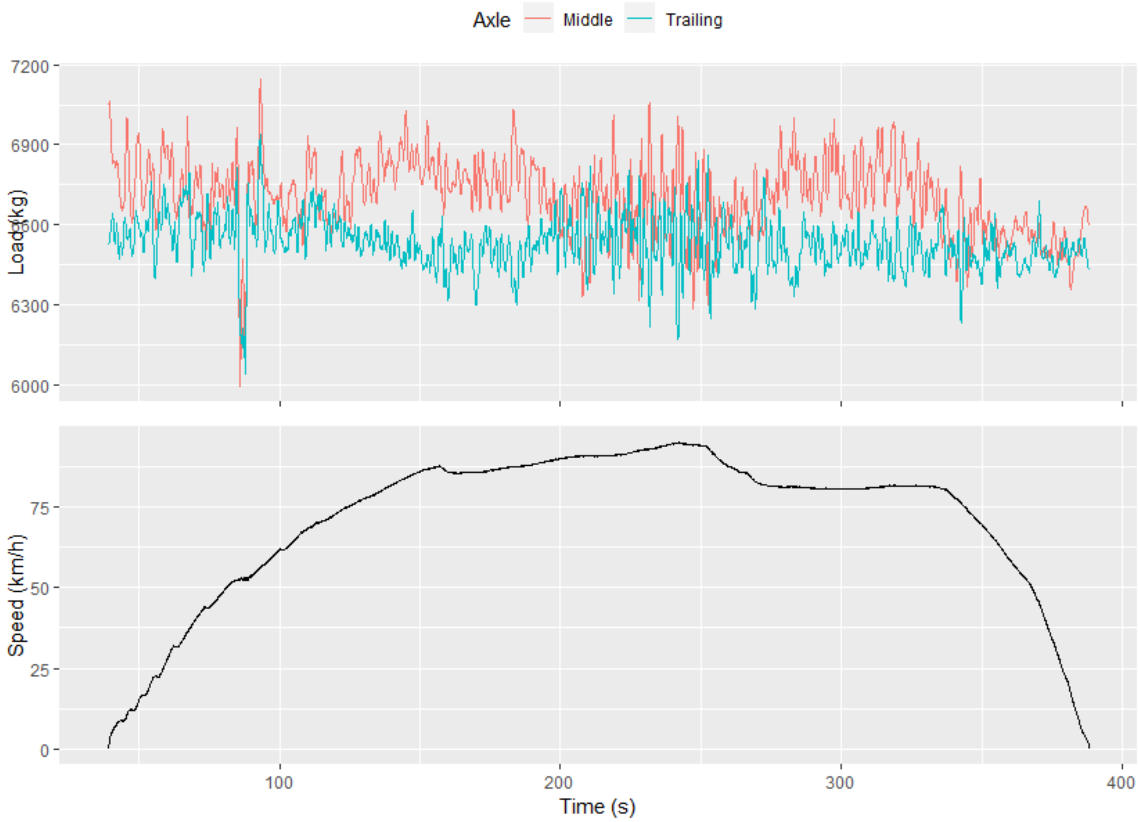
Kenworth

Kenworth 6X4 on Hot Lap at 0% Load

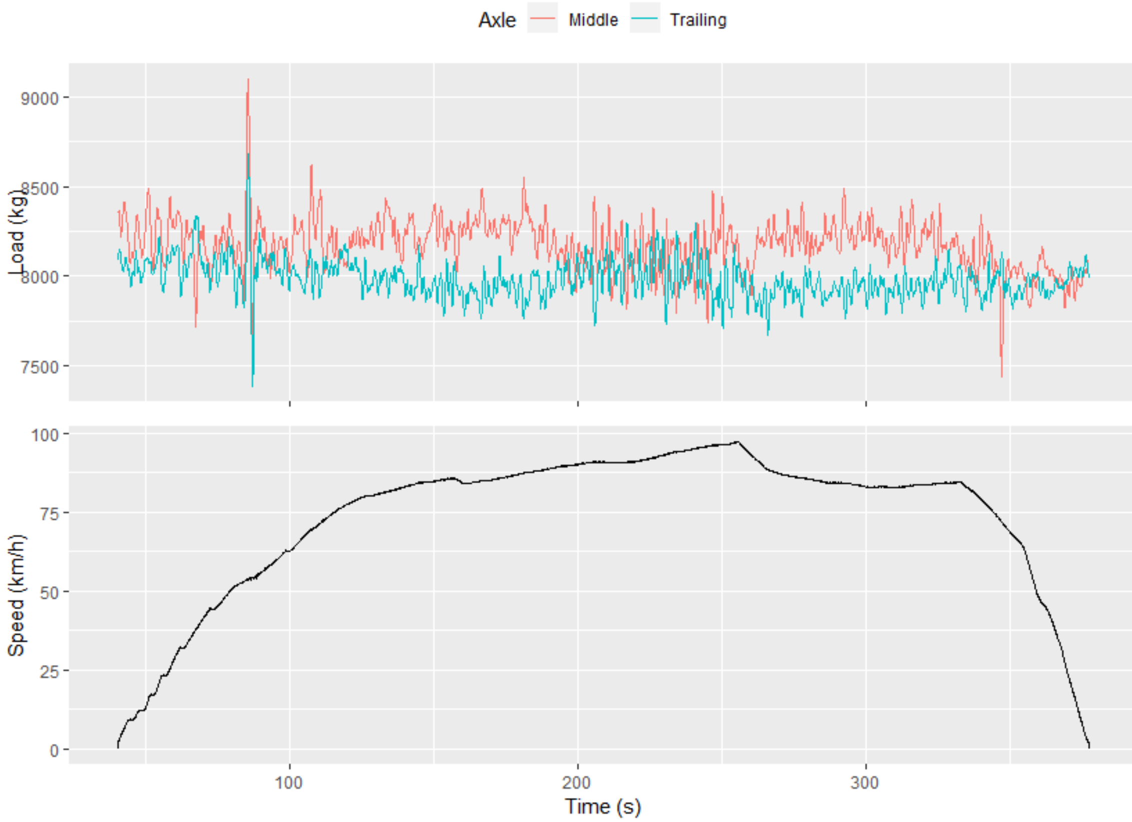
Kenworth 6X4 on Hot Lap at 50% Load



Kenworth 6X4 on Hot Lap at 70% Load

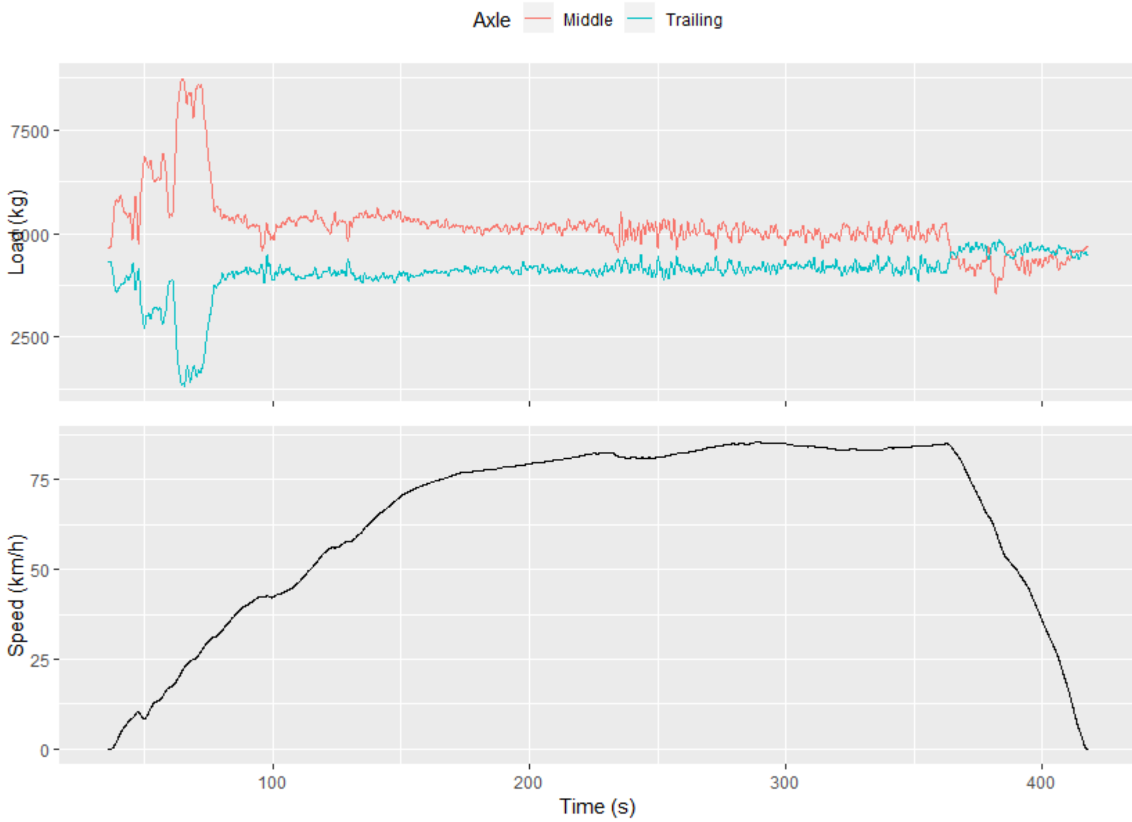


Kenworth 6X4 on Hot Lap at 85% Load



Kenworth 6X2 on Hot Lap at 0% Load

Kenworth 6X2 on Hot Lap at 50% Load

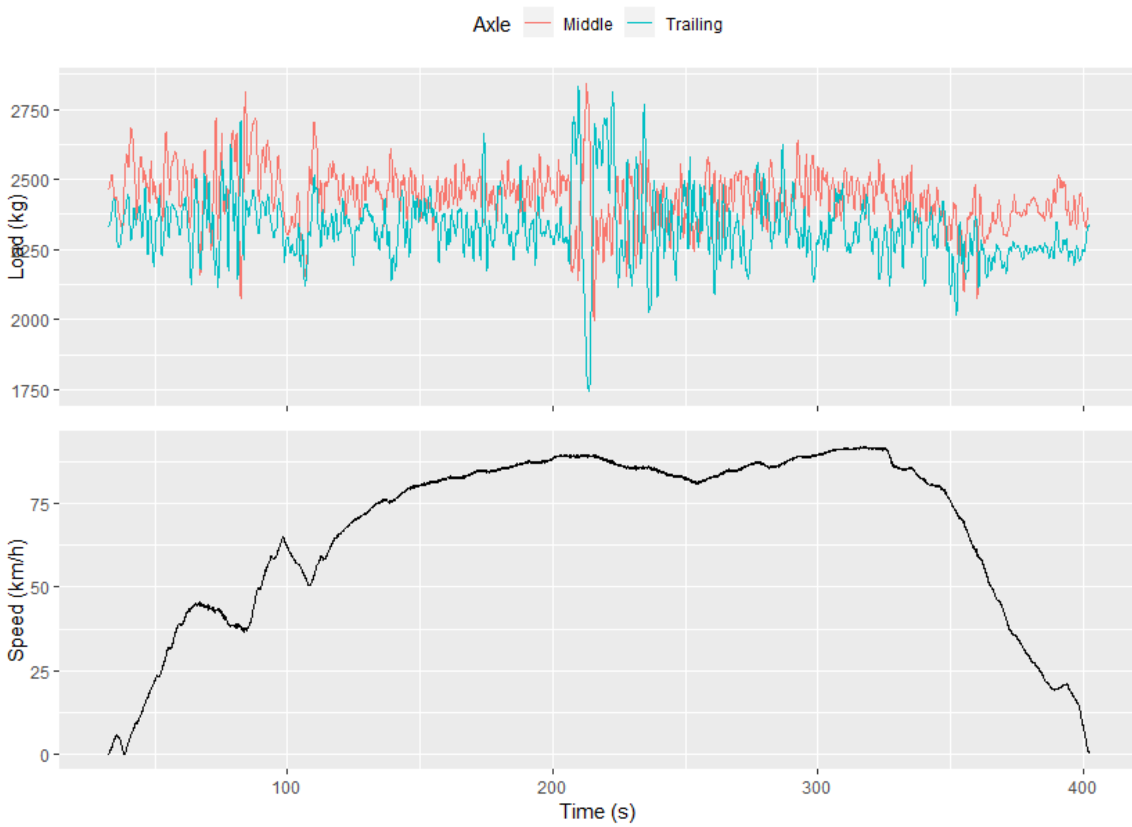


Kenworth 6X2 on Hot Lap at 70% Load

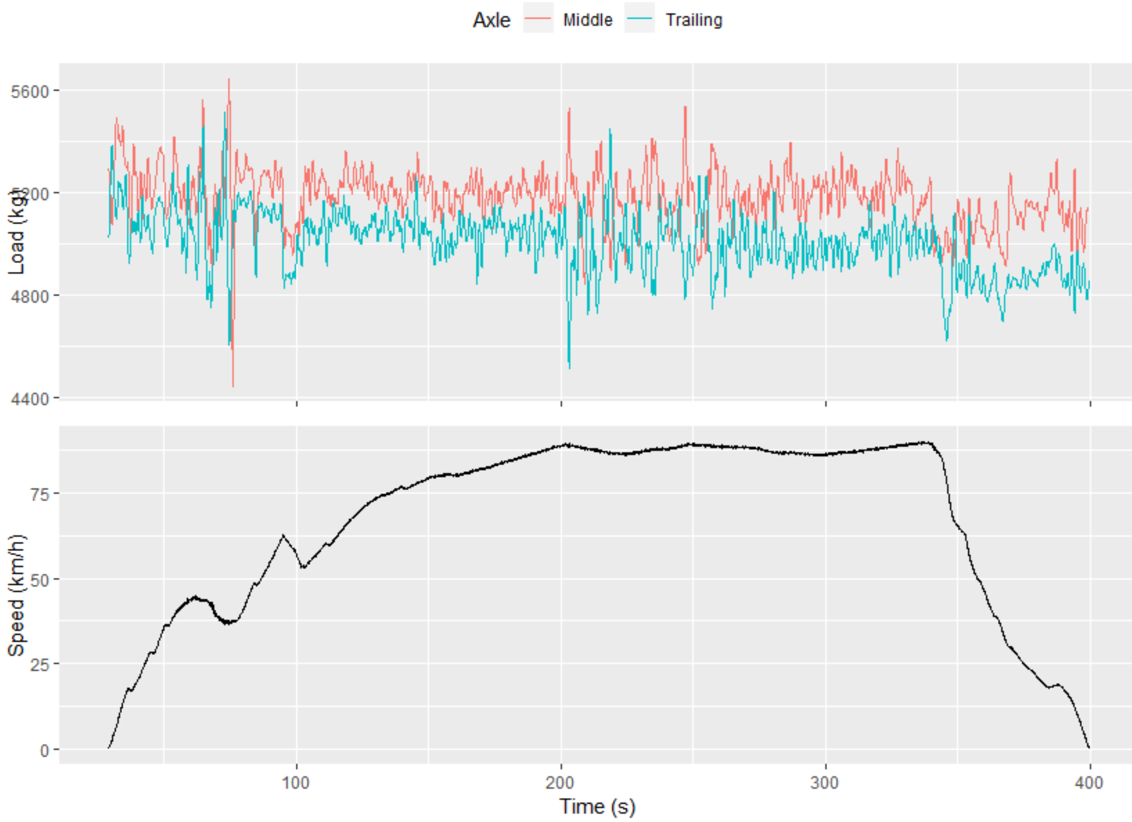
Kenworth 6X2 on Hot Lap at 85% Load

Volvo

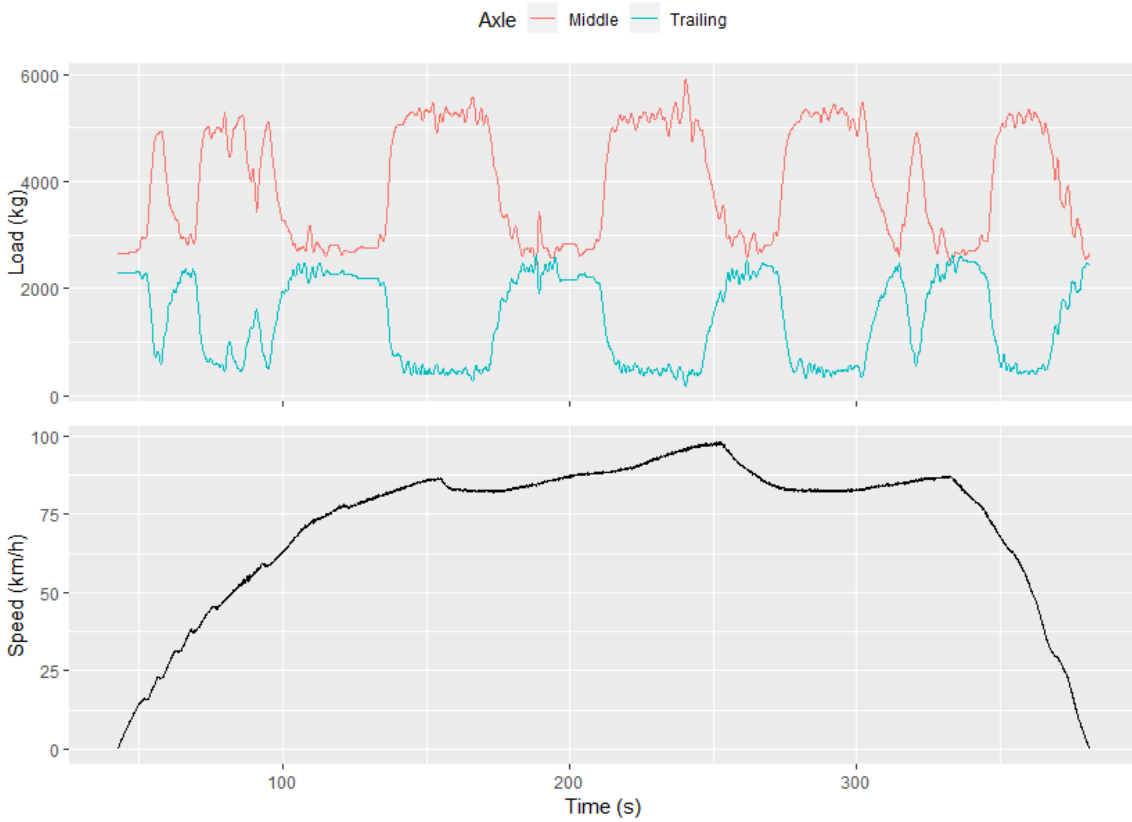
Volvo 6X4 on Hot Lap at 0% Load



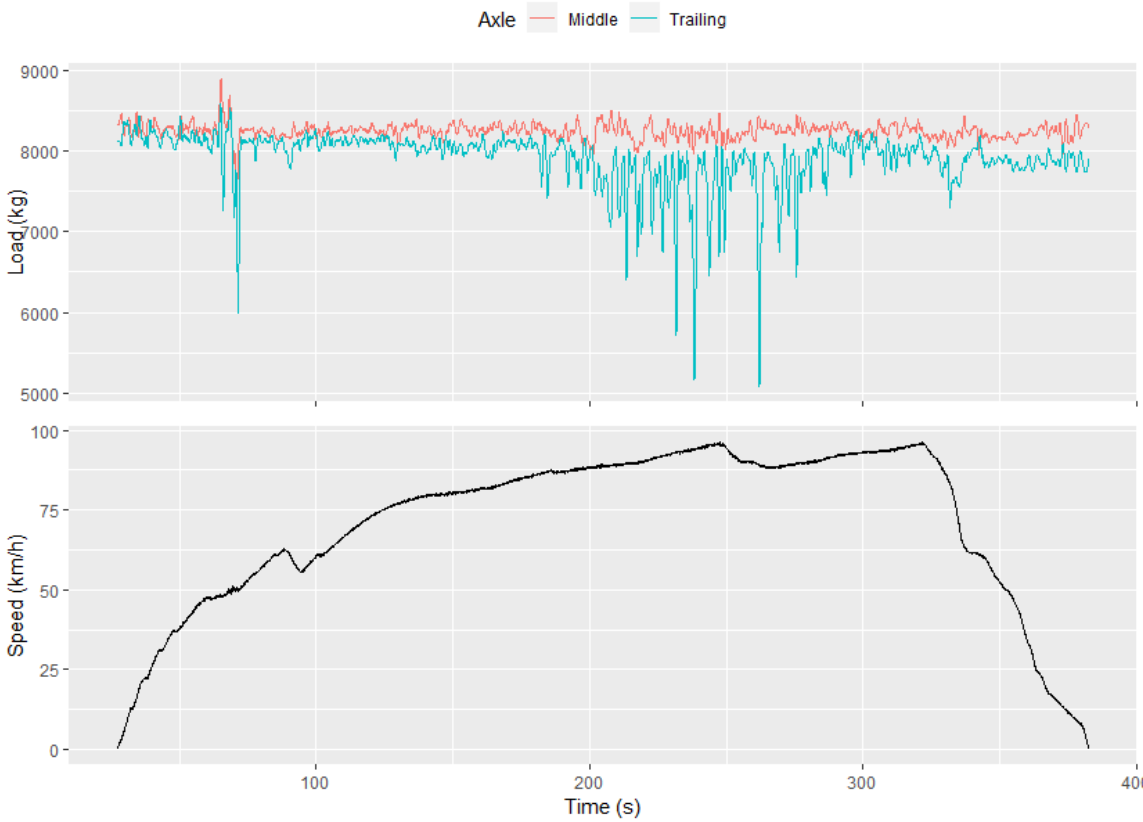
Volvo 6X4 on Hot Lap at 50% Load



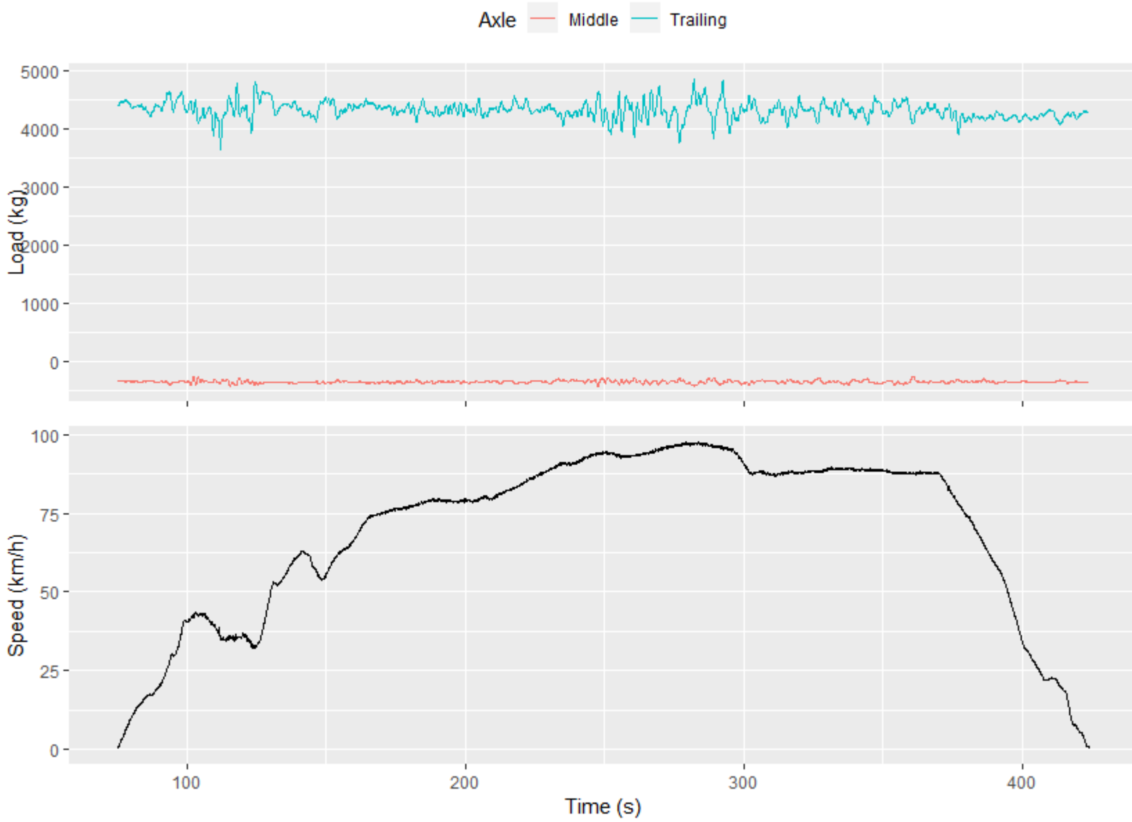
Volvo 6X4 on Hot Lap at 70% Load



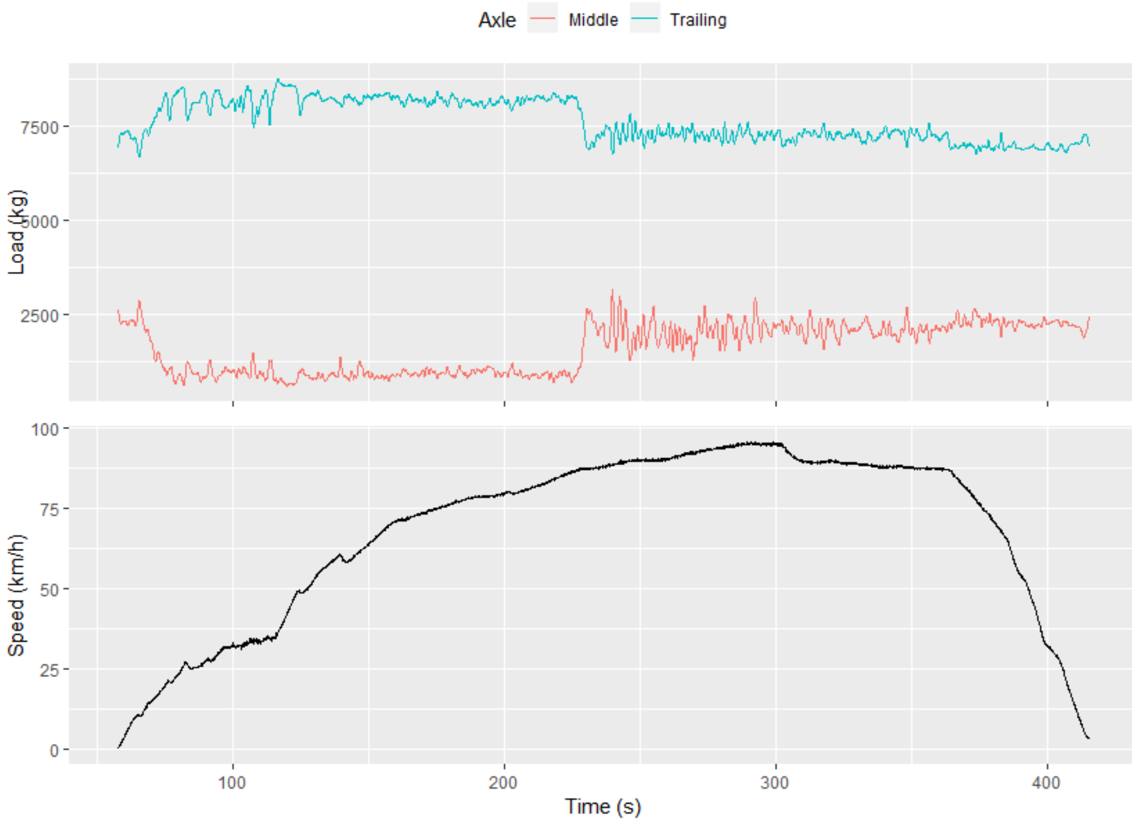
Volvo 6X4 on Hot Lap at 85% Load



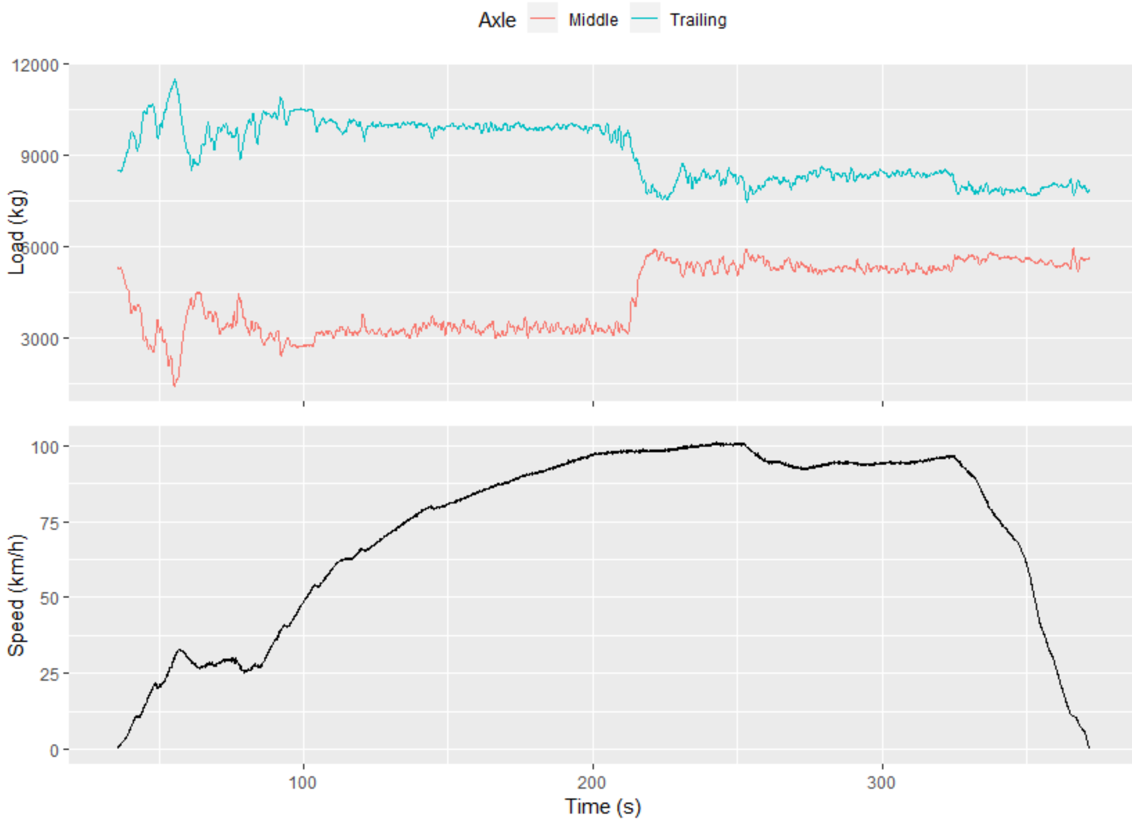
Volvo 6X2 on Hot Lap at 0% Load



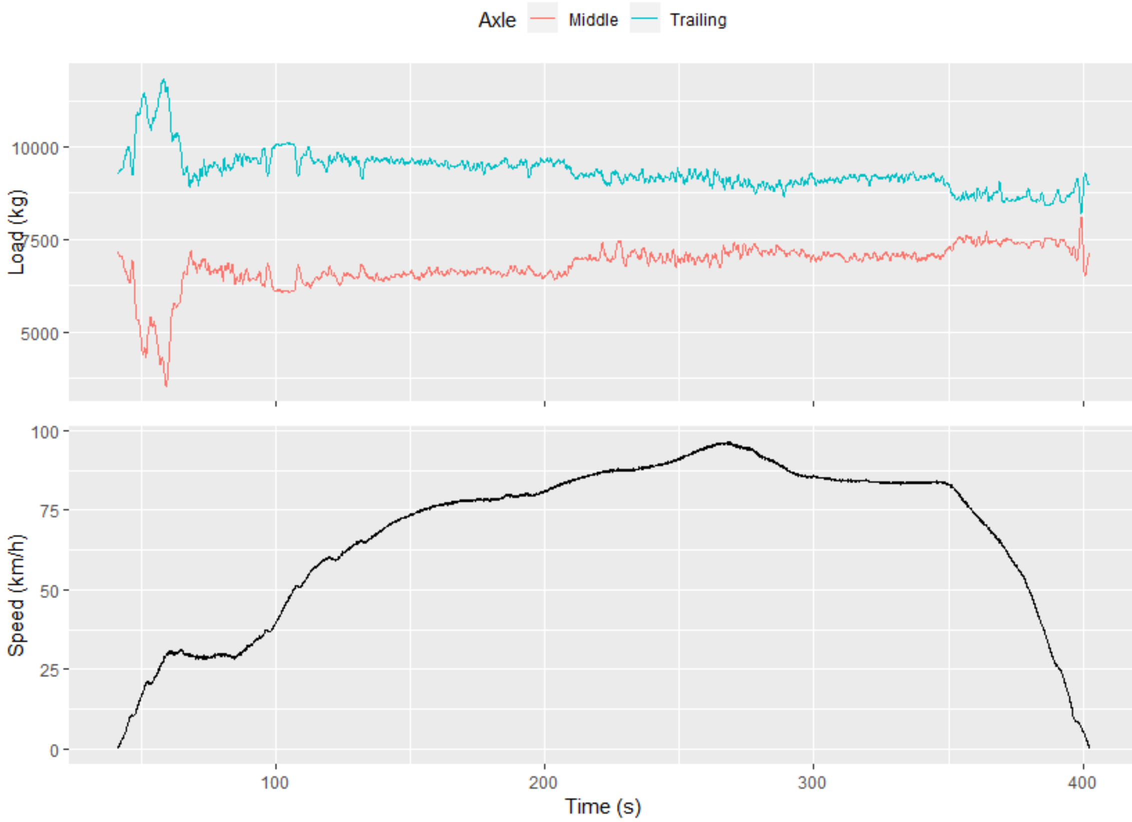
Volvo 6X2 on Hot Lap at 50% Load



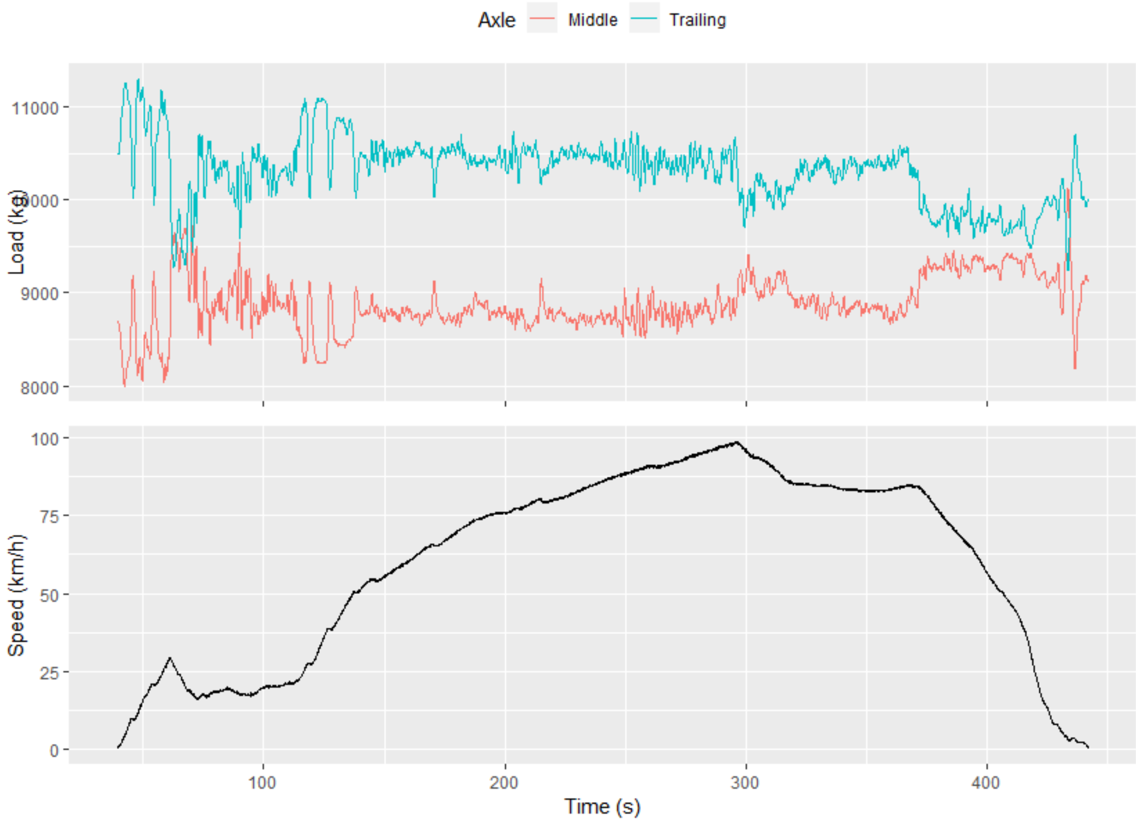
Volvo 6X2 on Hot Lap at 70% Load



Volvo 6X2 on Hot Lap at 85% Load



Volvo 6X2 on Hot Lap at 100% Load



Appendix D

Survey

Analysis of the Infrastructure Impacts of Heavy-duty Vehicle 6x2 Axle Technologies on Canadian Provincial and Territorial Roadways for Transport Canada (TC)

Use of a 6x2-axle configuration on highway tractors, as opposed to the more traditional 6x4-axle configuration, may lead to fuel savings and reductions in GHG emissions. The 6x2-axle design employs a single drive axle instead of the two drive axles employed by a conventional 6x4 system, thus eliminating the internal mechanical losses and mass associated with components such as the inter-axle drive shaft and differential.

With only one drive axle, however, tractors may suffer from reduced traction in certain conditions. To mitigate this problem, manufacturers offer systems capable of transferring load between the drive axle and the non-drive axle. This shift in loading may result in load levels beyond the current allowable limits in some provinces and territories.

Truck and traffic loading, environmental conditions, soil, and maintenance are key variables that affect pavement performance. With variable load systems that can transgress the allowable limits for loading, the potential for road surface damage opens up. Higher levels of road surface damage can also be amplified by seasonal shifts during the spring thaw. The North American Council for Freight Efficiency (NACFE) (2014) & The National Research Council Canada (2016) have examined loading configuration, fuel consumption, and traction in previous studies.

The objective of this work is to analyze and report on the potential impact of 6x2 load-shifting technologies on Canadian road infrastructure. Results should show the relationship between pavement degradation and 6x2 technology under a range of scenarios. Hence, it is necessary to obtain information from each jurisdiction regarding their pavement system and expectation with respect to the use of 6x2 vehicles.

Q1. By agreeing to participate in the study you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

□I agree to participate

□I do not agree to participate

Q2. What province are you representing?

□Alberta

□British Columbia

□Manitoba

□New Brunswick

□Newfoundland and Labrador

□Northwest Territories

□Nova Scotia

□Nunavut

□Ontario

□Prince Edward Island

□Quebec

□Saskatchewan

□Yukon

Q3. What organization are you representing and your role in the organization?

Q4. Which types of the road level are you expecting the 6x2 vehicle to run in your jurisdiction? (Please check all boxes that apply)

□Urban Highway

□Urban Expressway

□Urban Arterial road

□Urban Collector

□Urban Local road

□Rural Highway

□Rural Arterial road

□Rural Collector

□Rural Local

□Other (please specify)

Q5. What is the main pavement type currently in use in your jurisdiction for the roads specified in question #4? (Please check all boxes that apply)

□Flexible pavement

□Rigid pavement

□Gravel road

□Chip seal

□Other (please specify)

Q6. Please provide the proportion of each if there is more than one pavement type for the roads specified in question #5.

Q7. What is the typical pavement layer thickness for the roads specified in question #4?

Q8. What are the typical distresses you encounter for the roads specified in question #4? (Please check all boxes that apply)

□Fatigue cracking

□Permanent deformation / Rutting

□Raveling

□Bleeding

□Corrugation and Shoving

□Depression

□Longitudinal cracking

□Other (please specify)

Q9. Could you comment on the most significant distress and why?

Q10. What kind of pavement failure are you expecting might happen as a results of 6x2 vehicles in your jurisdiction, for the roads specified in question #4? (Please check all boxes that apply)

□Fatigue cracking

□Permanent deformation / Rutting

□Raveling

□Bleeding

□Corrugation and Shoving

□Depression

□Longitudinal cracking

□Other (please specify)

Appendix E

Example of ESAL Calculation

Kenworth – Highway at 100% load condition

Industry	Configuration	AADTT	Day	growth(0%)	DSF	LD	TF	years	ESAL
KW	**6x2 100% max tf**	20,000	365	1	0.5	0.7	5.837	1	14,913,535
	6x4 100% max tf	20,000	365	1	0.5	0.7	5.385	1	13,758,675
	6x2 100% avg tf	20,000	365	1	0.5	0.7	3.296	1	8,421,280
	6x4 100% avg tf	20,000	365	1	0.5	0.7	4.68	1	11,957,400
	6x2 100% min tf	20,000	365	1	0.5	0.7	2.099	1	5,362,945
	6x4 100% min tf	20,000	365	1	0.5	0.7	4.247	1	10,851,085

Kenworth – Major Arterial at 100% load condition

Industry	Configuration	AADTT	Day	growth(0%)	DSF	LD	TF	years	ESAL
KW	**6x2 100% max tf**	10,000	365	1	0.5	0.9	5.837	1	9,587,273
	6x4 100% max tf	10,000	365	1	0.5	0.9	5.385	1	8,844,863
	6x2 100% avg tf	10,000	365	1	0.5	0.9	3.296	1	5,413,680
	6x4 100% avg tf	10,000	365	1	0.5	0.9	4.68	1	7,686,900
	6x2 100% min tf	10,000	365	1	0.5	0.9	2.099	1	3,447,608
	6x4 100% min tf	10,000	365	1	0.5	0.9	4.247	1	6,975,698

Kenworth – Collector at 100% load condition

Industry	Configuration	AADTT	Day	growth(0%)	DSF	LD	TF	years	ESAL
KW	**6x2 100% max tf**	500	365	1	0.5	1	5.837	1	532,626
	6x4 100% max tf	500	365	1	0.5	1	5.385	1	491,381
	6x2 100% avg tf	500	365	1	0.5	1	3.296	1	300,760
	6x4 100% avg tf	500	365	1	0.5	1	4.68	1	427,050
	6x2 100% min tf	500	365	1	0.5	1	2.099	1	191,534
	6x4 100% min tf	500	365	1	0.5	1	4.247	1	387,539