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CHAPTER 6

FATIGUE FAILURE ANALYSIS AND LIFE EXPECTANCY

PROJECT 1

FATIGUE ANALYSIS OF WHEEL LUG STUD/WHEEL LUG BOLT

VEHICLE:

TOYOTA RAV4 XLE 2015

6.1 L4 LIFE EXPECTANCY USING COOK AND FATIGUE MODELS

From the previous chapters, we have observed that the lug studs different forces and moments act when a car goes through a turn. However, it is incredibly hard to identify how many turns a car takes in its lifetime. We will have to deduce this experimentally, as this is an information piece of information required for fatigue analysis of these lug studs. In order to do this, I took my home address and calculated the amount of turns taken to visit the different locations, in the categories of Long Distance, recreational, popular shops and restaurants. The number of turns and the distance to the destination is taken by looking at the fastest route provided by Google Maps. This information is provided in table 6.1-1.

Table 6.1-1: Distances and number of turns to different locations from home (Headington Hall)

	Start from	Destination	Distance (km)	Number of turns
Long Distance	Headington Hall	Oklahoma City	35.24	20
	Headington Hall	Tulsa	201.17	31
	Headington Hall	Edmond	55.52	26
Recreational	Headington Hall	Sooner Mall	6.44	8
	Headington Hall	Hey Day	14.48	13
	Headington Hall	Church	0.64	7
	Headington Hall	Warren Theatre	19.31	21
Popular shops	Headington Hall	Barnes and Nobles	4.83	9
	Headington Hall	Lowes	4.67	8
	Headington Hall	Walmart	4.51	12
	Headington Hall	Target	6.12	13
Restaurants	Headington Hall	Himalayas	19.31	12
	Headington Hall	Earth Café	1.29	7
	Headington Hall	McDonalds	5.63	7
	Headington Hall	Thai Kum Koon	3.54	8

These are some general places where I drive my car to. The average distance for all these destination is 25.51km and the average number of turns is 13.47.

On average, Americans drive a total of 21688 km per year[1]. Using this average, we can find that the total number of turns taken per year using equation 6.1-1.

$$\#\frac{turns}{year} = 21688\frac{km}{year} * \frac{13.47turns}{25.51km} = 11447\frac{turns}{year} \qquad (6.1\text{-}1)$$

Therefore, 11447 turns are taken per year by an average American according to our model. For this section, we are looking at a total of 10^4 cycles, therefore, the amount of time for 10^4 cycles is given by equation 6.1-2.

$$time\ (years) = \frac{10^4\ turns}{11447 \frac{turns}{year}} = 0.87\ years \tag{6.1-2}$$

This is a really small period of just 10 months. A lifetime of a car is somewhere around 15 years and in comparison to that, this value is really small. We would expect the safety factor to be calculated for such a short period of time to be really high.

Haigh Diagrams or Goodman relation are used to plot a relation between the alternating stress (y-axis) of these lug studs against the mean stress (x axis).[2] It is found that there is an inverse relationship between the two. The plot starts from the endurance stress and ends at the tensile stress. Whatveever the Se value is, that decides the slope of the graph. The graph shows that the mechanical component fails as the number of cycles increase moving to the right of the curve. This relation is shown in graph 6.1-1.

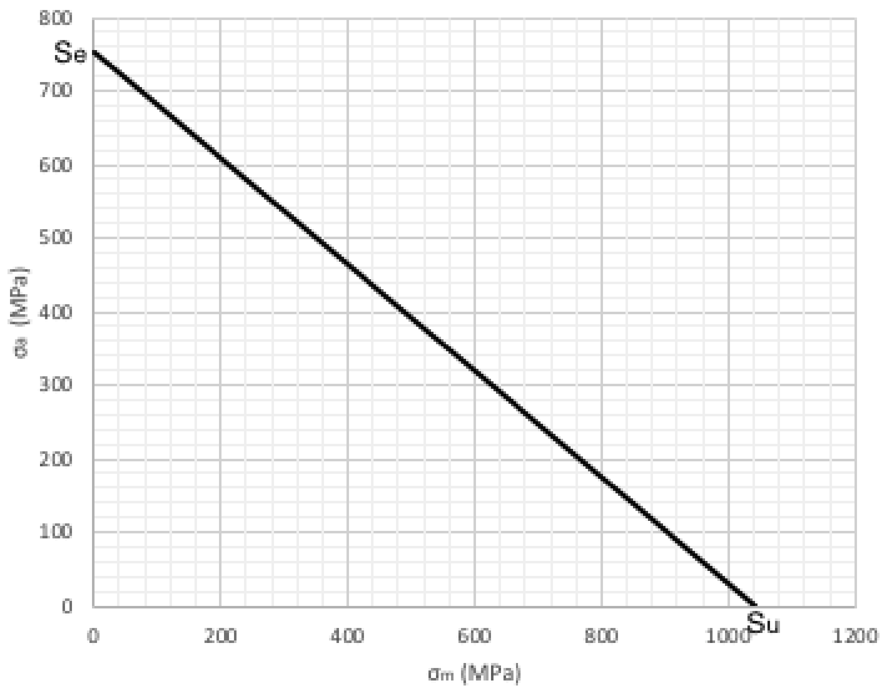

Figure 6.1-1: Haigh Diagram

In the next section, we are going to develop the Cook and Gunn model for L4 cycles, so that we can calculate the safety factors the stresses caused on lug stud for each speed.

6.1.1 L4 LIFE EXPECTANCY USING COOK FATIGUE MODEL

In this section, we will model the L4, which is 10,000 stress cycles using the Cook Fatigue Model. The table 6.1.1-1 provides all the parameters needed to calculate the Cook fatigue model for 10,000 cycles.

Table 6.1.1-1: L4 Cook Parameters

Notation	Parameter Description	English Units	Metric Units
S_u	Ultimate Tensile Strength	151 ksi	1040
S_y	Ultimate Yield Strength	136ksi	750.88
$-S_y$	Compressive Yield Strength	N/A	N/A
S_e	Endurance Limit	75.5 ksi	520
K_f	Fatigue Concentration Factor	3.31	3.31
K_t	Concentration notch	4.3	4.3
q	Notch Sensitivity Factor	0.7	0.7
C_L	Bending Load	1	1
	Axial Load	1	1
C_S	Surface Factor	1	1
C_G	Gradient factor	1	1
C_T	Temperature factor	1	1
C_R	Reliability factor	1	1

The first step is to calculate the endurance stress, which is given by equation 6.1.1-1.

$$S_e = C_L C_G C_S C_T C_R S_e' \tag{6.1.1-1}$$

As provided by Professor Harold Stalford, we are going to assume that all the above parameters (C_L, C_G, C_S, C_T and C_R) are 1 and, therefore, S_e = S_e'. Now to find the value of the endurance limit for 10^4 cycles, we know that S4/Su = 0.722 from the project description.

$$S_e = 0.722 S_u = 0.722 * 1040MPa = 750.88MPa \tag{6.1.1-2}$$

After this, the following parameters are required to perform a fatigue analysis (table 6.1.1-2). These have been calculated using the table 6.1.1-1.

Table 6.1.1-2: L4 Cook Fatigue Analysis Parameters

Parameter	Value
Kf/Su	0.0032
Sy / Kf	283.99
Se / Kf	226.85
Su/Kf	314.20
Sy/Su	0.90
Se/Su	0.72

Before we start plotting the Cook Fatigue Analysis, we need three parameters that are crucial in plotting the curve. These are:

$$S_a = \frac{S_e}{K_f}\left(\frac{1-\frac{S_y}{S_u}}{1-\frac{S_e}{S_u}}\right) \quad (6.1.1\text{-}3)$$

$$S_{m1} = \frac{S_y}{K_t} - S_a \quad (6.1.1\text{-}4)$$

$$S_{m2} = S_y - S_a \quad (6.1.1\text{-}5)$$

Table 6.1.1-3: Plot parameters

Parameter	Value
Sa	150.69
Sm1	133.29
Sm2	789.30

In table 6.1.1-3, we have used the equation 6.1.1-1 – 3 to find the value of the parameters. Once we have these parameters, we can finally use these values into the following equations to come up with our Cook Fatigue Plot.

$$\sigma_a = \frac{S_e}{K_f}\left(1 - \frac{K_f\sigma_m}{S_u}\right), 0 \leq \sigma_m \leq S_{m1} \quad (6.1.1\text{-}6)$$

$$\sigma_a = \frac{S_e}{K_f}\frac{\left(1-\frac{S_y}{S_u}\right)}{\left(1-\frac{S_e}{S_u}\right)}, S_{m1} \leq \sigma_m \leq S_{m2} \quad (6.1.1\text{-}7)$$

$$\sigma_a = S_y - \sigma_m, S_{m2} \leq \sigma_m \leq S_y \quad (6.1.1\text{-}8)$$

Using all of these equations and parameters, we can plot these curves on a σ_1-σ_2 plot like below in figure 6.1.1-1. The values are displayed on the graph.

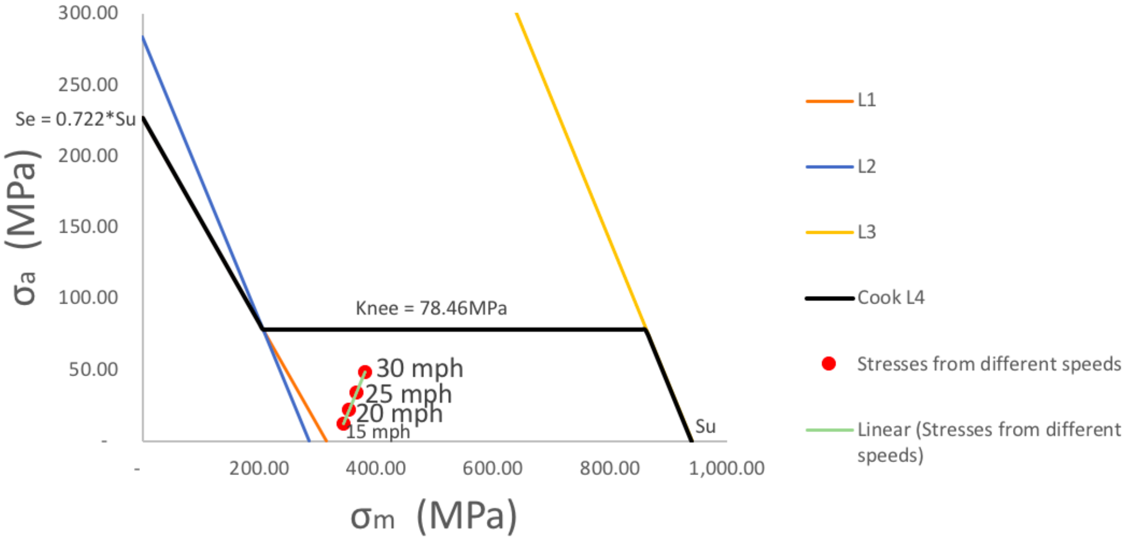

Figure 6.1.1-1: L4 Cook Plot

In the figure 6.1.1-1, the lines L1, L2 and L3 are used to plot the Cook diagram. The intersects of these lines decide the Cook plots' points. For further reference, please refer to citation [2].[3] In the figure above, the operating points for the different speeds have also been added. The bottom most point is 15mph, followed by 20, 20 and 30 mph. Since all of these points are under the curve, we can safely say that the lug studs will not fatigue in 10^4 cycles, that is, 0.87 years or 10 months. Therefore, we can calculate the safety factor for each of the operating points using the following equation 6.1.1-9.

$$SF = \frac{knee\ stress}{actual\ stress} \tag{6.1.1-9}$$

The table 6.1-4 below gives the safety factor for all the operating points.

Table 6.1.1-4: Safety Factor for different operating points

Speed (mph)	Mean stress (MPa)	Alternating Stress Actual (MPa)	Alternating Stress Cook (MPa)	Safety Factor
15	344.40	12.08	78.46	6.49
20	353.79	21.48	78.46	3.65
25	365.88	33.56	78.46	2.34
30	380.64	48.33	78.46	1.62

Since the safety factors are all above one, the graphical representation in figure 6.1.1-1 and table 6.1.1-4, suggest that all the speeds are safe for L4, that is, for 0.87 years. The user does not need to worry about the lug stud for at least, 1 year.

6.1.2 L4 LIFE EXPECTANCY USING GUNN FATIGUE MODEL

A similar process can be carried out for the Gunn Fatigue Model. Similar parameters in comparison to Cook models are needed for Gunn model. The only different is the use of K_t instead of K_f in Gunn Model. This value is already given in table 6.1.1-1. Since we are still looking at L4 cycles, the endurance limit is still 750.88 MPa, similar to the Cook model.

After this, the following parameters are required to perform a Gunn fatigue analysis (table 6.1.1-2). The only different from the Cook model is to now use K_t instead of K_f.

Table 6.1.2-2: L5 Gunn Fatigue Analysis Parameters

Parameters	Value
Sy / Se	1.25
Sy / Kt	218.60
Se / Kt	174.62
Su/Kt	241.86
Sy/Su	0.90
Se/Su	0.72

Our first goal is to find the S_a so that we can calculate all the other values based on that. S_a, we can find using the equation 6.1.2-1.

$$S_a = \frac{S_u}{K_t} X_N \tag{6.1.2-1}$$

X_N is a little hard to find. We have the formulae (equation 6.1.1-2 – 3) for it but we need to calculate the limit of the function and find the converging value as N goes to infinity.

$$X_N = \frac{\left[\frac{S_y}{S_e} - 1\right]}{\left[\frac{S_u}{S_e} - 1\right]} \tag{6.1.2-2}$$

$$X_{N+1} = \frac{\left[\frac{S_y}{S_e} - 1\right] + \left[X_N^{4/3} - X_N\right]}{\left[\frac{S_u}{S_e} - 1\right]} \tag{6.1.2-3}$$

The value of X_{N+1} converges really fast. These have been shown in the table 6.1.2-3 below.

Table 6.1.2-3: Convergence of X_n Values

X	Value
0	0.65412286
1	0.42998972
2	0.38027489
3	0.38202381
4	0.38187268
5	0.38188548
6	0.38188439
7	0.38188448
8	0.38188448
9	0.38188448

The value of X converges to 0.382 only after 4 values in 3 significant figures. The other values are shown to measure in different in 8 significant figures. After this, the following equations are used to develop the Gunn Model.

$$\sigma_a = \frac{S_e}{K_t}\left(1 - \left(\frac{K_f \sigma_m}{S_u}\right)^{4/3}\right), 0 \leq \sigma_m \leq S_a \tag{6.1.2-5}$$

$$\sigma_a = \sigma_a^*, S_a \leq \sigma_m \leq S_y \tag{6.1.2-6}$$

Table 6.1.2-4: L4 Gunn Plot Parameters

Parameters	Value
Sa	92.36
σ_a	126.24

Using all of these parameters, we can calculate the Gunn Plot in the figure 6.1.2-1 below with all the operating points of different speeds.

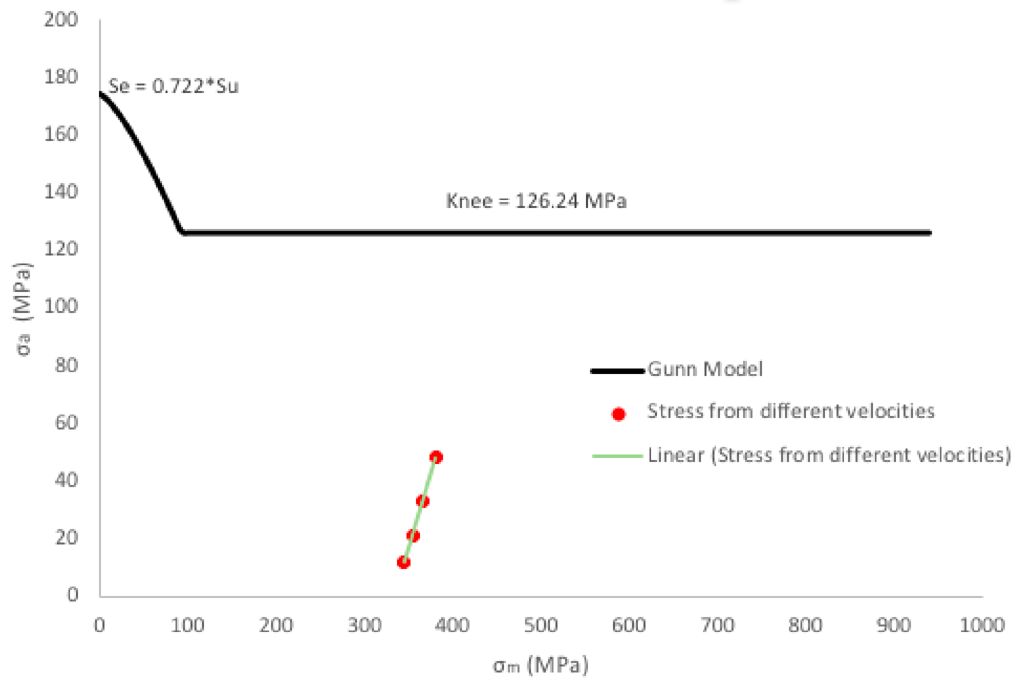

Figure 6.1-2-1 L4 Cook Fatigue Plot

As we can see from the figure 6.1.2-1, all the operating points for different speeds are under the curve. This is very similar to the L4 Cook plot. Therefore, we would expect the Safety factor (calculated from equation 6.1.1-9) to be all well above 1. S.F. have been provided in the table below for all the different speeds.

Table 6.1.1-5: Safety Factors from L4 Gunn Fatigue Model

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	126.24	10.45
20	21.48	126.24	5.88
25	33.56	126.24	3.76
30	48.33	126.24	2.61

As expected, the safety factors from the L4 Gunn model are all well above 1, which means the lug stud for Toyota RAV4 XLE 2015 is completely safe from any fatigue failure in 0.87 years or 10 months for speeds of up to 30mph.

Through a Fatigue analysis from Cook and Gunn model, we can conclude that for speeds up to 30mph, the lug stud in the car is free from fatigue failure.

6.2 L5 LIFE EXPECTANCY USING COOK AND FATIGUE MODELS

Very similar to the section 6.1, we can now calculate the life of a lug stud for L5, that is, 100,000 cycles. Using the equations 6.1-1 – 2, we can again calculate the number of years it would take a car to meet 100,000 cycles in its lifetime.

$$time\ (years) = \frac{10^5\ turns}{11447\,\frac{turns}{year}} = 8.7\ years = 8\ years\ and\ 8\ months \qquad (6.2\text{-}1)$$

The average life of a car, according to consumerreport.org is about 8 years[4]. Therefore, L5 should be the most accurate prediction of a true lug stud life. Let's observe this with Cook and Gunn Models.

6.2.1 L5 LIFE EXPECTANCY USING COOK FATIGUE MODEL

Since we are using the same lug stud, all parameters except the endurance limit, stay exactly the same as table 6.1.1-1. Endurance limit, as defined in the project description for 100,000 cycles is:

$$S_e = 0.611 S_u = 0.611 * 1040MPa = 635.44MPa \qquad (6.2.1\text{-}1)$$

As we can see in the pattern, the endurance limit is decreasing with an increase in cycles. This should make the graphs move down, closer to the different speed operating points we have. Now we can calculate the parameters needed to carry out the Cook Fatigue Analysis (table 6.2.1-1). This is very similar to table 6.1.1-2.

Table 6.2.1-1: L5 Cook Fatigue Analysis Parameters

Parameters	Value
Kf/Su	0.0032
Sy / Kf	283.99
Se / Kf	191.98
Su/Kf	314.20
Sy/Su	0.90
Se/Su	0.611

Again, similar to section 6.1.1, we can use the equations 6.1.1-3 – 5, to find the Cook plot parameters. These have been provided in the table 6.2.1-2 below.

Table 6.2.1-2: L5 Cook plot parameters

Parameter	Value
Sa	47.45
Sm1	236.53
Sm2	892.55

Once we have these parameters, we can finally use these values into the equations 6.1.1-6 – 8 to come up with our Cook Fatigue Plot.

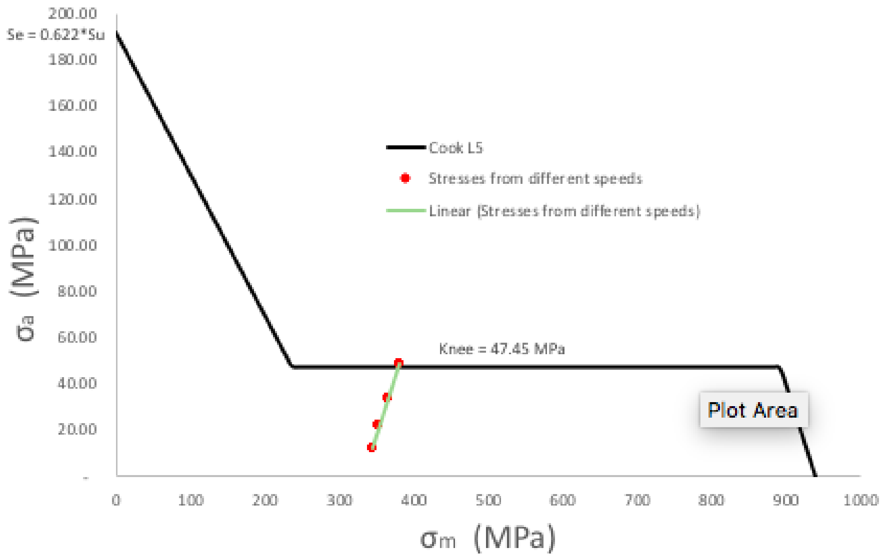

Figure 6.2.1-1: L5 Cook Fatigue Analysis plot

Unlike figure 6.1.1-1, there are more features to notice in figure 6.2.1-1. Firstly, line L1, L2 and L3 have been hidden so that the focus is on the graph and the operating points. We can see from the figure 6.2.1-1 above, that only the first 3 operating points are under the curve. This is something we need to be concerned about. The fourth point is for 30mph. This point is just above the knee. Let us try to calculate the safety factors for each of the points and observe the results (table 6.2.1-3).

Table 6.2.1-3: L5 Safety factors for different operating points

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	47.45	3.93
20	21.48	47.45	2.21
25	33.56	47.45	1.41
30	48.33	47.45	0.98

As it can be seen from the table 6.2.1-3 above, the 30mph speed is just on the range of the plot. The safety factors are below 1 for 30mph and therefore, this means that we should change the lug studs every 8.7 years for safety purposes according to the Cook Fatigue Model.

6.2.2 L5 LIFE EXPECTANCY USING GUNN FATIGUE MODEL

This section will cover the 100,000 cycles of lug stud and fatigue analysis using the GUnn fatigue model. A very similar process to L5 Cook fatigue model can be carried for the L5 Gunn Fatigue Model. Once again, the only difference of use in parameters is use of K_t instead of K_f. All the other values are already given in table 6.1.1-1. Since we are still looking at L5 cycles, the endurance limit is still 635.44 MPa, similar to the L5 Cook model above in section 6.2.1.

After this, the following parameters are required to perform a Gunn fatigue analysis (table 6.2.1-2). The only different from the Cook model is to now use K_t instead of K_f.

Table 6.2.2-1: L4 Gunn Fatigue Analysis Parameters

Parameters	Value
Sy/Se	1.48
Sy / Kt	218.60
Se / Kt	147.78
Su/Kt	241.86
Sy/Su	0.90
Se/Su	0.611

Similar to 6.1.2, we will first S_a using the equation 6.1.2-1 so that we can calculate all the other values based on that. The convergence of X_{N+1} is shown in the table 6.2.2-2 below.

Table 6.2.2-2: Convergence of X_n Values

X	Value
0	0.75281788
1	0.6460391
2	0.61529762
3	0.60837374
4	0.60693905
5	0.60664759
6	0.60658862
7	0.6065767
8	0.60657429
9	0.60657381
10	0.60657371
11	0.60657369

The value of X converges to 0.607 only after 4 values in 3 significant figures. The other values are shown to measure in different in 8 significant figures. After this, we can use equation 6.1.2-5 – 6 to plot the L5 Gunn Fatigue model.

Table 6.2.2-3: L5 Gunn Plot Parameters

Parameters	Value
Sa	92.36
σ_a	126.24

Using these two parameters, we can calculate the Gunn Plot in the figure 6.2.2-1 below with all the operating points of different speeds.

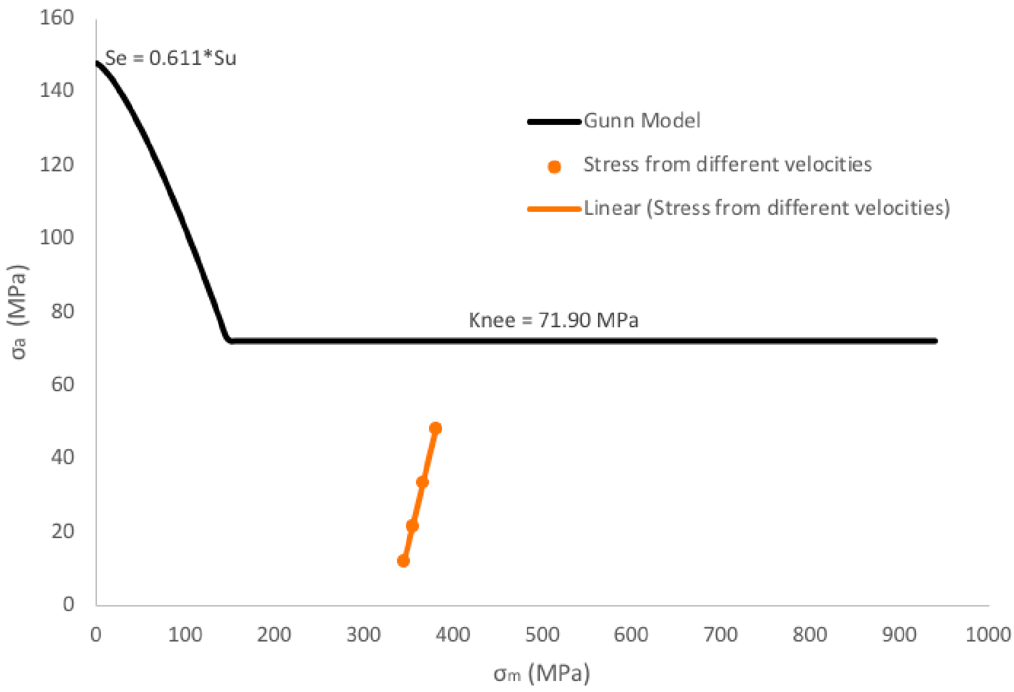

Figure 6.2-2-1 L5 Cook Fatigue Plot

As we can see from the figure 6.2.2-1, all the operating points for different speeds are under the curve. This is very similar to the L4 Gunn plot but different from L5 Cook plot. Therefore, we would expect the Safety factor (calculated from equation 6.1.1-9) to be all well above 1. S.F. have been provided in the table below for all the different speeds.

Table 6.2.2-4: Safety Factors from L5 Gunn Fatigue Model

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	71.90	5.95
20	21.48	71.90	3.35
25	33.56	71.90	2.14
30	48.33	71.90	1.49

The results are very different from L5 Cook Fatigue Model. In this case, all the Safety Factors are above 1, indicating that the life of a lug stud for 8.7 years for speeds of upto 30 mph is safe.

Through a Fatigue analysis from Cook and Gunn model, we can conclude that the Cook model is a more conservative one. Even the lowest factor from Gunn model is well above 1 at 1.49 (table 6.1.4-4). As designers, since 30 mph is in a shady region, we should still consider about the safety of the passenger and get the lug stud replaced every 8.7 years.

6.3 L6 LIFE EXPECTANCY USING COOK AND FATIGUE MODELS

Very similar to the section 6.1, we can now calculate the life of a lug stud for L6, that is, 1,000,000 cycles. Using the equations 6.1-1 – 2, we can again calculate the number of years it would take a car to meet 1,000,000 cycles in its lifetime.

$$time\ (years) = \frac{10^6\ turns}{11447\,\frac{turns}{year}} = 87.4\ years = 87 years\ and\ 4 months \qquad (6.3\text{-}1)$$

Since the average life of a car is only 8 years,[2] continuing with this L6 cycle is redundant, as it would be an anomaly if a person still uses the car after 87 years. This is why L6 is called the infinite cycle. Generally, these cars are antiques and not used to the same extent and therefore, equation 6.3-1 will fail the assumption. We should expect to see a lot of points above the failure knee stress.

However, for the sake of the project requirement, we will continue the Cook and Gunn Fatigue Analysis of L6 – infinite cycle.

6.3.1 L6 LIFE EXPECTANCY USING COOK FATIGUE MODEL

Since we are using the same lug stud as the previous sections, all parameters except the endurance limit, stay exactly the same as table 6.1.1-1. Endurance limit, as defined in the project description for 1,000,000 cycles is:

$$S_e = 0.5 S_u = 0.5 * 1040MPa = 520MPa \qquad (6.3.1\text{-}1)$$

As mentioned in section 6.2.1 that the endurance limit is decreasing in every cycle, we observe that it is even lower of just 520 MPa for an infinite cycle. We would expect to see more point above the failure knee in this section. Similar to before, the parameters needed to calculate the Cook Fatigue Analysis are laid down in table 6.3.1-1.

Table 6.3.1-1: L6 Cook Fatigue Analysis Parameters

Parameters	Value
Kf/Su	0.0032
Sy / Kf	283.99
Se / Kf	157.10

Su/Kf	314.20
Sy/Su	0.90
Se/Su	0.50

Again, similar to section 6.1.1, we can use the equations 6.1.1-3 – 5, to find the Cook plot parameters. These have been provided in the table 6.3.1-2 below.

Table 6.3.1-2: L6 Cook plot parameters

Parameter	Value
Sa	30.21
Sm1	253.78
Sm2	909.79

Once we have these parameters, we can finally use these values into the equations 6.1.1-6 – 8 to come up with our Cook Fatigue Plot figure 6.3.1-1.

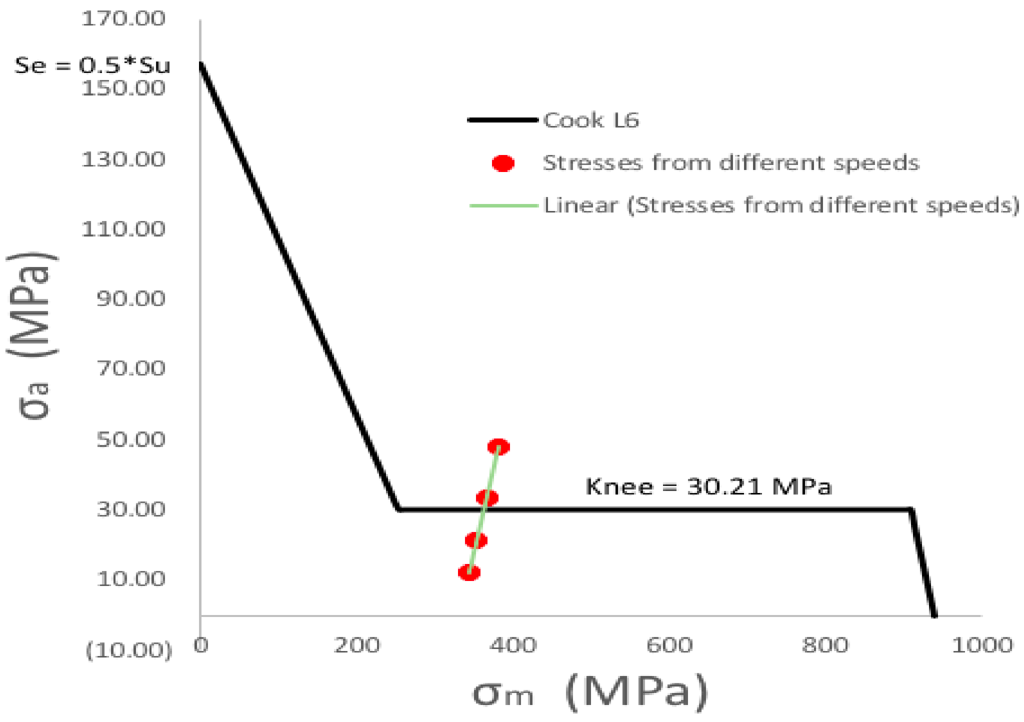

Figure 6.3.1-1: L5 Cook Fatigue Analysis plot

Once again, L1, L2 and L3 have been hidden so that the focus is on the graph and the operating points. We can see from the figure 6.3.1-1 above, that only the first 2 operating points are under the curve. This is something we need to be concerned about. The third and fourth point is for 25mph and 30mph. Before making any conclusion, let us first come up with our safety factors.

Table 6.3.1-3: L6 Safety factors for different operating points

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	30.21	2.50
20	21.48	30.21	1.41
25	33.56	30.21	0.90
30	48.33	30.21	0.63

This is a change from before, but we were expecting an even more drastic result. Ceteris paribus, if the car survives with the same average use for 87 years and does not go above the speed of 20mph, we would expect the lug stud to survive for such a long life. From a safety standpoint, we should still change the lug studs every 8.7 years as mentioned in section 6.2.2.

6.3.2 L6 LIFE EXPECTANCY USING GUNN FATIGUE MODEL

This section will cover the 1,000,000 cycles of lug stud and fatigue analysis using the Gunn fatigue model – a process very similar to section 6.1.2 and 6.2.2. The endurance limit, as specified by the project description is 540MPa, same as in section 6.3.1.

The following L6 Gunn Fatigue Analysis parameters are required to perform a Gunn fatigue analysis (table 6.3.1-2).

Table 6.3.2-1: L6 Gunn Fatigue Analysis Parameters

Parameters	Value
Sy/Se	1.81
Sy / Kt	218.60
Se / Kt	120.93
Su/Kt	241.86
Sy/Su	0.903
Se/Su	0.5

Similar to 6.1.2, we will first S_a using the equation 6.1.2-1 so that we can calculate all the other values based on that. The convergence of X_{N+1} is shown in the table 6.3.2-2 below.

Table 6.3.2-2: Convergence of X_n Values

X	Value
0	0.80769231
1	0.75219065
2	0.73957695
3	0.73693829

4	0.73639721
5	0.73628673
6	0.73626419
7	0.73625959
8	0.73625865
9	0.73625846
10	0.73625842
11	0.73625841

The value of X converges to 0.736 only after 4 values in 3 significant figures. The other values are shown to measure in different in 8 significant figures. After this, we can use equation 6.1.2-5 – 6 to plot the L6 Gunn Fatigue model.

Table 6.2.2-3: L5 Gunn Plot Parameters

Parameters	Value
Sa	92.36
σ_a	126.24

Using these two parameters, we can calculate the Gunn Plot in the figure 6.3.2-1 below with all the operating points of different speeds.

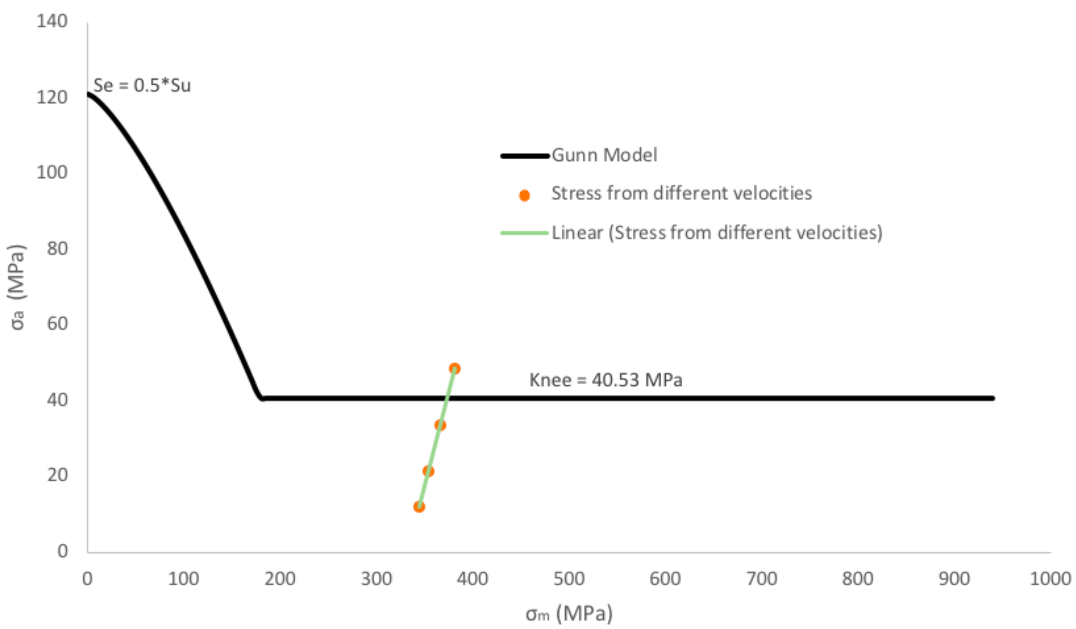

Figure 6.3-2-1 L6 Cook Fatigue Plot

As we can see from the figure 6.3.2-1, only 1 operating point is above the knee of 40.53MPa. In the Cook plot for L6, two speeds were above the knee. Let us calculate the safety factors before any other conclusions.

Table 6.3.3-4: Safety Factors from L5 Gunn Fatigue Model

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	40.53	3.35
20	21.48	40.53	1.89
25	33.56	40.53	1.21
30	48.33	40.53	0.84

The results are in a way similar to Cook plot but also different. Only one point is below 0 in terms of safety factor, while the others are all in the safe region. According to the Gunn Fatigue Analysis, if a car runs for 87 years with upto 25mph on each drive, there would be problem in changing the lug stud for the complete life of the wheels and the car.

Once again, we can see that the Cook fatigue model is considerably more conservative. As designers, I think we should go with the results of section 6.2.2, where it is stated that the lug stud should be changed every 8.7 years for the safety.

All the cook plots have been added onto a single graph and it can be seen below in figure 6.3.2-2.

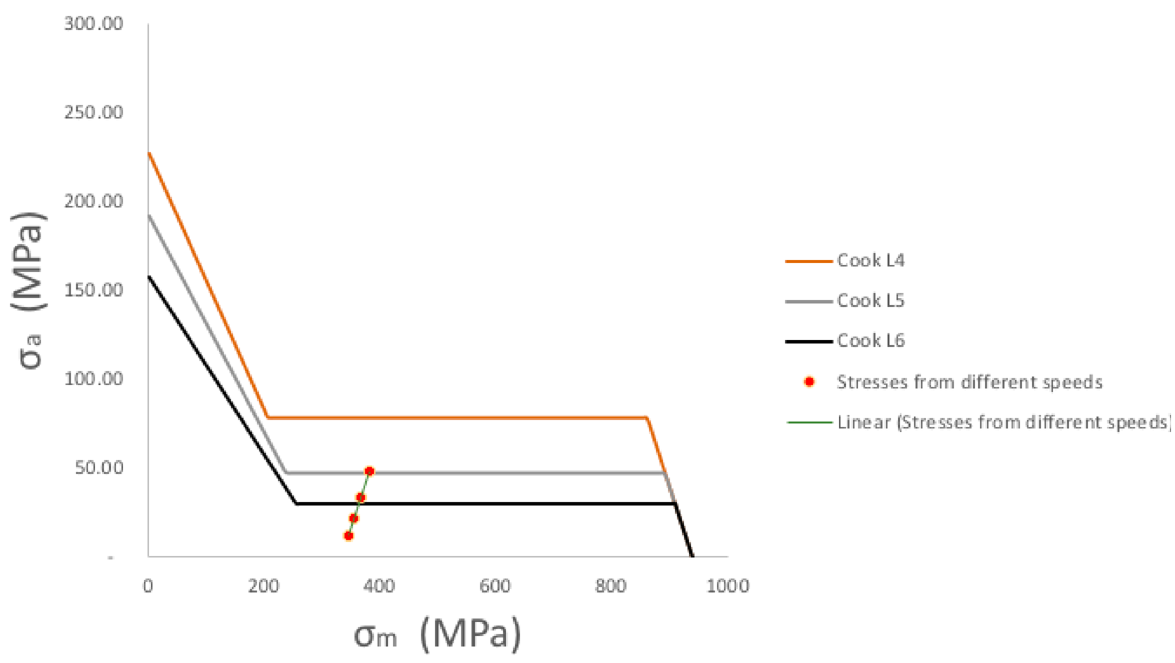

Figure 6.3.2-2: L4, L5 and L6 Cook plots

All the calculations done in this chapter are based on speeds of only upto 30 mph. This is a clear short-coming in the book. Addressing higher speeds need to be addressed later, as more complicated models are required for that.

6.4 TABLE OF DATA AND RESULTS

Table 6.1-4: Distances and number of turns to different locations from home (Headington Hall)

	Start from	Destination	Distance (km)	Number of turns
Long Distance	Headington Hall	Oklahoma City	35.24	20
	Headington Hall	Tulsa	201.17	31
	Headington Hall	Edmond	55.52	26
Recreational	Headington Hall	Sooner Mall	6.44	8
	Headington Hall	Hey Day	14.48	13
	Headington Hall	Church	0.64	7
	Headington Hall	Warren Theatre	19.31	21
Popular shops	Headington Hall	Barnes and Nobles	4.83	9
	Headington Hall	Lowes	4.67	8
	Headington Hall	Walmart	4.51	12
	Headington Hall	Target	6.12	13
Restaurants	Headington Hall	Himalayas	19.31	12
	Headington Hall	Earth Café	1.29	7
	Headington Hall	McDonalds	5.63	7
	Headington Hall	Thai Kum Koon	3.54	8

Table 6.1.1-1: L4 Cook Parameters

Notation	Parameter Description	English Units	Metric Units
S_u	Ultimate Tensile Strength	151 ksi	1040
S_y	Ultimate Yield Strength	136ksi	750.88
$-S_y$	Compressive Yield Strength	N/A	N/A
S_e	Endurance Limit	75.5 ksi	520
K_f	Fatigue Concentration Factor	3.31	3.31
K_t	Concentration notch	4.3	4.3
q	Notch Sensitivity Factor	0.7	0.7
C_L	Bending Load	1	1
	Axial Load	1	1
C_S	Surface Factor	1	1
C_G	Gradient factor	1	1
C_T	Temperature factor	1	1
C_R	Reliability factor	1	1

Table 6.1.1-2: L4 Cook Fatigue Analysis Parameters

Parameter	Value
Kf/Su	0.0032
Sy / Kf	283.99
Se / Kf	226.85
Su/Kf	314.20
Sy/Su	0.90
Se/Su	0.72

Table 6.1.1-3: Plot parameters

Parameter	Value
Sa	150.69
Sm1	133.29
Sm2	789.30

Table 6.1.1-4: Safety Factor for different operating points

Speed (mph)	Mean stress (MPa)	Alternating Stress Actual (MPa)	Alternating Stress Cook (MPa)	Safety Factor
15	344.40	12.08	78.46	6.49
20	353.79	21.48	78.46	3.65
25	365.88	33.56	78.46	2.34
30	380.64	48.33	78.46	1.62

Table 6.1.2-2: L5 Gunn Fatigue Analysis Parameters

Parameters	Value
Sy / Se	1.25
Sy / Kt	218.60
Se / Kt	174.62
Su/Kt	241.86
Sy/Su	0.90
Se/Su	0.72

Table 6.1.2-3: Convergence of X_n Values

X	Value
0	0.65412286

1	0.42998972
2	0.38027489
3	0.38202381
4	0.38187268
5	0.38188548
6	0.38188439
7	0.38188448
8	0.38188448
9	0.38188448

Table 6.1.2-4: L4 Gunn Plot Parameters

Parameters	Value
Sa	92.36
σ_a	126.24

Table 6.1.1-5: Safety Factors from L4 Gunn Fatigue Model

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	126.24	10.45
20	21.48	126.24	5.88
25	33.56	126.24	3.76
30	48.33	126.24	2.61

Table 6.2.1-1: L5 Cook Fatigue Analysis Parameters

Parameters	Value
Kf/Su	0.0032
Sy / Kf	283.99
Se / Kf	191.98
Su/Kf	314.20
Sy/Su	0.90
Se/Su	0.611

Table 6.2.1-2: L5 Cook plot parameters

Parameter	Value
Sa	47.45
Sm1	236.53

Sm2	892.55

Table 6.2.1-3: L5 Safety factors for different operating points

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	47.45	3.93
20	21.48	47.45	2.21
25	33.56	47.45	1.41
30	48.33	47.45	0.98

Table 6.2.2-1: L4 Gunn Fatigue Analysis Parameters

Parameters	Value
Sy/Se	1.48
Sy / Kt	218.60
Se / Kt	147.78
Su/Kt	241.86
Sy/Su	0.90
Se/Su	0.611

Table 6.2.2-2: Convergence of X_n Values

X	Value
0	0.75281788
1	0.6460391
2	0.61529762
3	0.60837374
4	0.60693905
5	0.60664759
6	0.60658862
7	0.6065767
8	0.60657429
9	0.60657381
10	0.60657371
11	0.60657369

Table 6.2.2-3: L5 Gunn Plot Parameters

Parameters	Value
Sa	92.36
σ_a	126.24

Table 6.2.5-4: Safety Factors from L5 Gunn Fatigue Model

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	71.90	5.95
20	21.48	71.90	3.35
25	33.56	71.90	2.14
30	48.33	71.90	1.49

Table 6.3.1-1: L6 Cook Fatigue Analysis Parameters

Parameters	Value
Kf/Su	0.0032
Sy / Kf	283.99
Se / Kf	157.10
Su/Kf	314.20
Sy/Su	0.90
Se/Su	0.50

Table 6.3.1-2: L6 Cook plot parameters

Parameter	Value
Sa	30.21
Sm1	253.78
Sm2	909.79

Table 6.3.1-3: L6 Safety factors for different operating points

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	30.21	2.50
20	21.48	30.21	1.41
25	33.56	30.21	0.90

30	48.33	30.21	0.63

Table 6.3.2-1: L6 Gunn Fatigue Analysis Parameters

Parameters	Value
Sy/Se	1.81
Sy / Kt	218.60
Se / Kt	120.93
Su/Kt	241.86
Sy/Su	0.903
Se/Su	0.5

Table 6.3.2-2: Convergence of X_n Values

X	Value
0	0.80769231
1	0.75219065
2	0.73957695
3	0.73693829
4	0.73639721
5	0.73628673
6	0.73626419
7	0.73625959
8	0.73625865
9	0.73625846
10	0.73625842
11	0.73625841

Table 6.2.2-3: L5 Gunn Plot Parameters

Parameters	Value
Sa	92.36
σ_a	126.24

As we can see from the figure 6.3.2-1, only 1 operating point is above the knee of 40.53MPa. In the Cook plot for L6, two speeds were above the knee. Let us calculate the safety factors before any other conclusions.

Table 6.3.6-4: Safety Factors from L5 Gunn Fatigue Model

Speed (mph)	Alternating Stress Actual (MPa)	Knee Stress (MPa)	Safety Factor
15	12.08	40.53	3.35
20	21.48	40.53	1.89
25	33.56	40.53	1.21
30	48.33	40.53	0.84

6.5 REFERENCES

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[3] Burguete, R L, and E A Patterson. "The Effect of Mean Stress on the Fatigue Limit of High Tensile Bolts Burguete, R.L. and Patterson, E.A. Proc. Inst. Mech. Eng B, J. Engng Manufacture (1995) 209 (C4), 257â"262 ISSN: 0954-4054." International Journal of Fatigue, vol. 19, no. 5, 1997, p. 441., doi:10.1016/s0142-1123(97)90094-3.

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6.6 LEVEL OF EFFORT

For this project, I think I spent about 20 hours in total getting everything finished, firstly on Sunday, then on Tuesday.