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Wheel Hub Fatigue Performance under Non-constant Rotational Loading and Comparison to Eurocycle Test

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Abstract

Wheel Eurocycle (EC) loading condition could be adapted to hub as a result of similar loading characteristics on vehicle. A correlation is constructed between road load data (RLD) for specified vehicles and EC test spectrum. To provide correlation between EC and RLD, test speed, axial and lateral loads at EC are converted to cyclic loading condition and relevant loading scenarios are generated. Rotational effect is taken into account. Pseudo-damage results of RLD and EC spectra are compared and expected fatigue lifetime for hub is presented.

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Keywords:Wheel & Hub Assembly, Eurocycle,RLD,Component Testing, Rotational Loading Scenario.

1. Introduction

Nowadays, complexity reduction is an important aspect for vehicle manufacturers therefore commonization between vehicle lines is a must. That arises from the necessity of cost reduction so that the manufacturers can compete in the market. Verification with tests is the most traditional way to do this. However, test cost also has to be taken into account. Also, engineering specifications and requirement communization has an important role to cope with cost

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restrictions. The validation of modern passenger vehicle wheels is generally carried out by using a procedure as applying the specific two or three dimensional constant amplitude loadings which models the real life of component. A better way to simulate the real life of component is achieved by proving grounds. The test rig mileage as 7500 km should be fulfilled without any crack. [1] Corner module has different critical parts, which typically consist of wheel, hub and bearing that should be tested on dynamic loading condition. Even these parts have similar loading characteristics; they are still tested on different complex test rigs which have higher operating cost. The Eurocycle load spectra provides wheel manufacturers with a standard test load sequence that is adapted to the biaxial wheel test rig developed by Fraunhofer. [2] The idea behind this study is that the wheel loading cycles of Eurocycle norms will gain the ability of covering hub loading spectra. It must be remembered that the mechanism of failure acts differently for the hub and wheel because of the material variance. For heavy commercial vehicles, it is generally observed that while hub has a more brittle behavior, wheel has a more ductile fracture mechanism. Wheels have unique designs which are not directly related to loading conditions as the same wheel can be used on different vehicle lines and even different axles on same vehicle. Therefore, they are needed to be sufficiently safe enough to cope with a relatively wide loading spectrum. Eurocycle offers a scaleable test load sequence for individual wheels based on the data which is obtained while running vehicle durability schedules [3]. The biaxial tests provide us to apply variable radial and lateral loads through the wheel hub assembly. The loads are transferred directly from wheel to hub through studs and it gives a chance to commonize the component tests of different parts in the assembly. Hubs also have unique designs as wheels which have common usage at different vehicle lines and even different positions on same vehicle. This reveals the idea of using the similar loading spectrum for the whole components of the wheel hub assembly. On the other hand, the loadings applied to hub are different from each other for each different vehicle line and for part’s location at the vehicle. As a result of this condition, road load data are collected for each vehicle during pre-design phase and vehicle durability sign-off is given with respect to fatigue analyses of every part. Although this analysis acceptance criterion is valid for general durability aspects, the unexpected overloads resulting from customer’s usage can result risky conditions for safety critical designs. Also, the broadness of vehicle line makes the data acquisition process harder. The aim of the study is to understand the difference between a test procedure which is accepted by a wide range of vehicle manufacturer and specific road load data of vehicle types as illustrated at Figure 1.

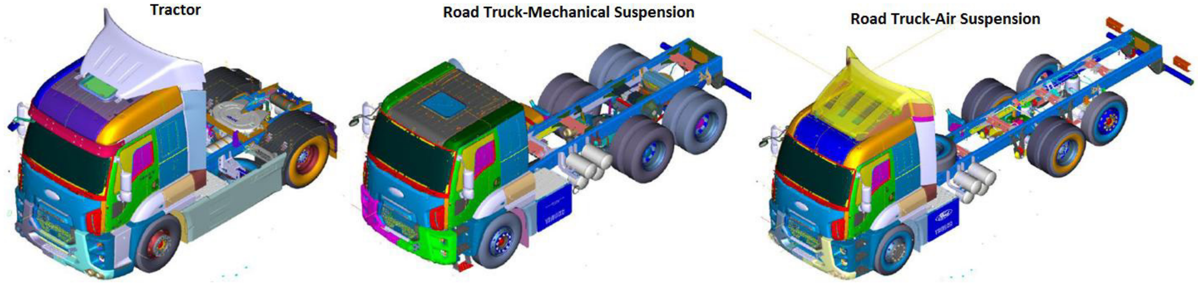


Figure 1: Vehicle types

2. Methodology

2.1. Loading Spectrum

Eurocycle has 98 different events which consist of vertical and lateral blocked load-time history. These values are determined with respect to wheel dimensions and loading rates [3] and Eurocycle II [4] standards. Road load data, which are collected at eight different axles from three different vehicles and could be simply defined as a random loading, are evaluated to obtain a correlation between Eurocycle test procedures. By this comparison, different usages of same component are classified with respect to load basis. WFT are used to provide loads applied to the vehicle by road. For this purpose, four wheel force transducer are mounted to the vehicle in the same way as a standard wheel to measure force and moments. Vehicle combinations are selected to be able to represent wide range of loading characteristics adequately. Load data of air suspended tractor, air suspended road truck and road truck with mechanical suspension are used to understand the scope. These vehicles are to be shown at Figure 1. Road load data could be defined as random load history. An algorithm is used to model the rotational aspect of time varying load. Input load have seven channels as $F_x(t)$, $F_y(t)$, $F_z(t)$, $M_x(t)$, $M_y(t)$, $M_z(t)$ and wheel angle (α) as illustrated at Figure 2.

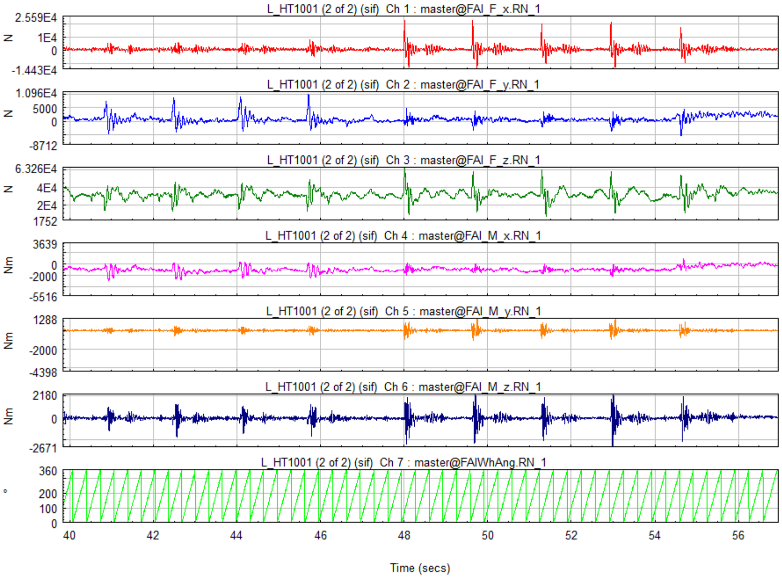


Figure 2: Random road load data with wheel angle

The rotational effect is modelled by the algebraic equations given below. The output of this algorithm is illustrated at Figure 3.

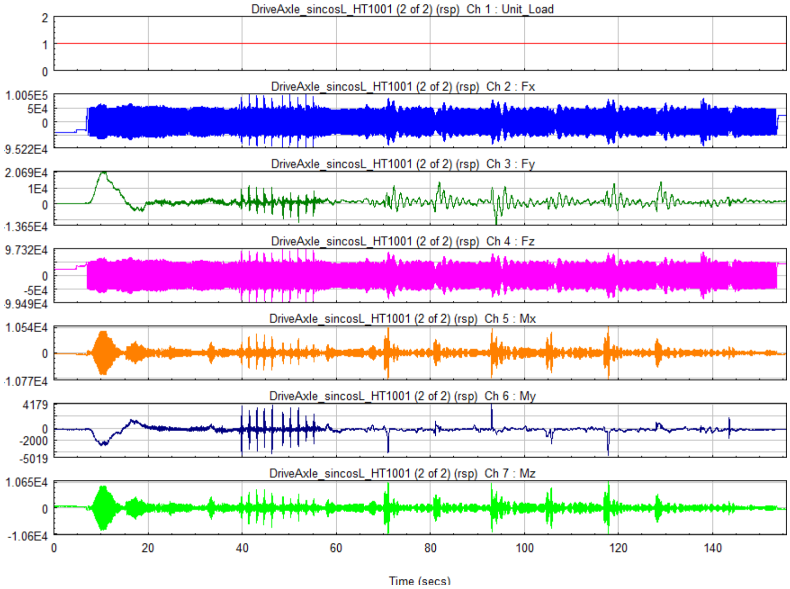


Figure 3: Rotational model of road load data with unit force channel

$$F_{unit} = \mathrm{F}_x(\mathrm{t}).0 + 1 \qquad (1)$$

$$F_{x,r}(t) = \mathrm{F}_x(\mathrm{t}).\cos(\alpha) + \mathrm{F}_y(\mathrm{t}).\sin(\alpha) \qquad (2)$$

$$F_{y,r}(t) = \mathrm{F}_y(\mathrm{t}) \tag{3}$$

$$F_{z,r}(t) = \mathrm{F}_x(\mathrm{t}).\sin(\alpha) + \mathrm{F}_y(\mathrm{t}).\cos(\alpha) \tag{4}$$

$$M_{x,r}(t) = \mathrm{M}_x(\mathrm{t}).\cos(\alpha) + \mathrm{M}_y(\mathrm{t}).\sin(\alpha) \tag{5}$$

$$M_{y,r}(t) = \mathrm{M}_y(\mathrm{t}) \tag{6}$$

$$M_{z,r}(t) = \mathrm{M}_x(\mathrm{t}).\sin(\alpha) + \mathrm{M}_y(\mathrm{t}).\cos(\alpha) \tag{7}$$

F_{unit} is required as the pre-load stress from finite element input and is to be scaled by “1”. In that way, the pre-stress comes from finite element analysis only. $F_{x,r}(t)$ is the rotational and time dependent force at x-direction. $F_{y,r}(t)$ is time dependent load at y-direction as $F_y(t)$ does not change with respect to rotation. $F_{z,r}(t)$ is the rotational and time dependent load at z-direction. Other three channels as $M_{x,r}(t)$, $M_{y,r}(t)$, $M_{z,r}(t)$ are the moments. For all events, this algorithm is used and the resulting time dependent rotationally modelled load data are used at duty cycle procedure. Eurocycle specification consists of 98 events which are illustrated at Table 1. Vertical and lateral loads are applied by biaxial test machine as shown at Figure 4. Tyre radius is used to transport the lateral force to the center of hub as moment. Variable tyre radius which is defined as a function of load magnitude with static load radius (SLR) empirical equation is used.

Table 1: Eurocycle test specification

EUROCYCLE - WHEEL TEST SPECIFICATION

Event No	Fv [kN]	Fl [kN]	Tyre Radius(mm)	Cycle	Event No	Fv [kN]	Fl [kN]	Tyre Radius(mm)	Cycle	Event No	Fv [kN]	Fl [kN]	Tyre Radius(mm)	Cycle
1	45	0	518.8125	112	34	54	7.2	513.975	69	67	30	-12	526.875	18
2	60	33	510.75	38	35	54	-7.2	513.975	69	68	48	0	517.2	62
3	30	9	526.875	92	36	76	0	502.15	64	69	30	-12	526.875	24
4	45	0	518.8125	270	37	51	0	515.5875	63	70	48	0	517.2	50
5	75	34.8	502.6875	38	38	42	0	520.425	5352	71	66	33	507.525	13
6	45	0	518.8125	37	39	66	30	507.525	32	72	36	0	523.65	43
7	69.6	38.4	505.59	26	40	42	-12	520.425	130	73	72	33	504.3	51
8	39	-9	522.0375	105	41	48	0	517.2	156	74	51	0	515.5875	146
9	63	28.8	509.1375	89	42	48	21.6	517.2	12	75	78	14.4	501.075	71
10	30	-9	526.875	104	43	39	0	522.0375	68	76	76	-14.4	502.15	71
11	60	33	510.75	95	44	48	27	517.2	25	77	54	7.2	513.975	69
12	45	0	518.8125	353	45	39	0	522.0375	289	78	54	-7.2	513.975	69
13	46.56	18	517.974	237	46	60	32.4	510.75	44	79	78	0	501.075	65
14	37.2	0	523.005	80	47	45	6	518.8125	81	80	51	0	515.5875	63
15	55.2	25.2	513.33	82	48	36	-12	523.65	31	81	48	0	517.2	63
16	30	-12	526.875	55	49	45	6	518.8125	62	82	30	-12	526.875	43
17	45	12	518.8125	249	50	30	-12	526.875	31	83	60	27.6	510.75	76
18	84	24	497.85	65	51	45	0	518.8125	75	84	42	12	520.425	285
19	60	27.6	510.75	88	52	102	46.8	488.175	26	85	66	30	507.525	32
20	27	-9	528.4875	55	53	40.8	-9	521.07	118	86	64.6	0	508.2775	5448
21	45	3	518.8125	199	54	66	30	507.525	25	87	84	38.4	497.85	13
22	66	30	507.525	76	55	51	12	515.5875	38	88	48	12	517.2	81
23	66	30	507.525	13	56	60	33.6	510.75	19	89	30	-12	526.875	116
24	42	-4.5	520.425	124	57	30	-12	526.875	12	90	42	0	520.425	1118
25	42	12	520.425	25	58	42	0	520.425	31	91	48	18	517.2	37
26	60	36	510.75	19	59	30	-12	526.875	18	92	48	0	517.2	50
27	42	-7.5	520.425	173	60	46	21.6	518.275	12	93	60	18	510.75	25
28	84	38.4	497.85	13	61	36	-12	523.65	55	94	42	-12	520.425	37
29	42	0	520.425	166	62	66	33	507.525	25	95	48	24	517.2	12
30	78	36	501.075	51	63	36	-12	523.65	12	96	30	-12	526.875	12
31	52	0	515.05	146	64	48	0	517.2	87	97	54	25.2	513.975	13
32	78	14.4	501.075	71	65	36	-12	523.65	55	98	45	0	518.8125	187
33	78	-14.4	501.075	71	66	66	33	507.525	44					

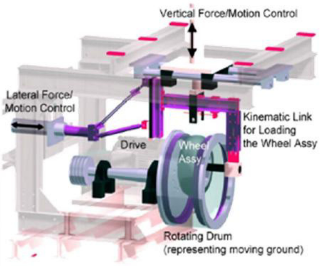


Figure 4: Biaxial test machine

2.2. Finite Element Analysis

Finite element model is constructed with commercial FEA software, Abaqus. The software is selected because of its achievements with contact algorithm. The model consists of two bearings, a spindle, an axle and the hub as illustrated at Figure 5. It is a representative model for all axles. The rotational aspect is modelled and the time varying characteristics of loadings are modelled at a commercial post process program, ncode Designlife.

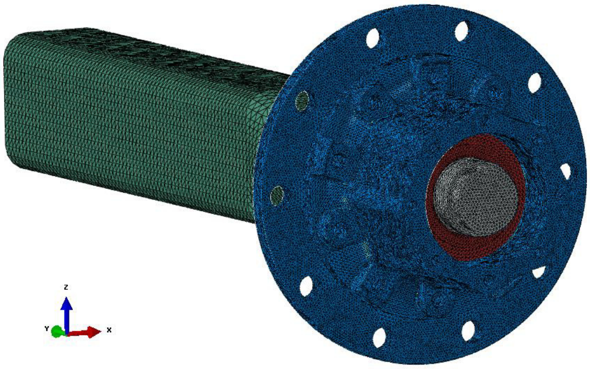


Figure 5: Finite element model of hub assembly

Axisymmetric boundary conditions are used. Shrink fit condition between the hub and the bearings are modelled with respect to maximum and minimum tolerances of bearings, hub and spindle. Second order elements, C3D10, are used in order to improve the accuracy and the stress output is requested for hub only. During the contact solving process at finite element software, discontinuous stress results may occur. The artificial strain energy of model needs to be checked with respect to strain energy and total work in order to get rid of false models. Most accurate model is selected within consideration of artificial strain energy percentage needs to be under 1% for accurate models. Shear locking and hourglass control is not necessary as the analyzed part has second order tetrahedral elements. Unit load analysis, which is defined as the analysis consists of unit magnitude loads at each degree of freedom (DOF), needs to be done in order to determine the stress state of hub under unit loads at each DOF. At this type of analysis, a unit load is applied at all DOFs one by one and as a result, the stress state of the part is obtained at every DOF. Each step of analysis "must" contains only one stress state because they will be matched with their time varying characteristics on post process. For example, at uniaxial loading (when excitation is at only one direction), the finite element input analysis needs to consist of:

- Step 1: Preload; σ_{pr}
- Step 2: Stress resulting from F=1; $\sigma_{pr} + \sigma_{load}$

Step 1 contains the effects of preloads (shrink fit and nut pretension) whereas Step 2 also contains preload but in addition to Step 1 it contains the stress response of part to applied load too. The effect of preload at step 2 needs to be removed before the post process as these steps are matched with time varying loads. If model needs to consist of more steps, it is expected that after the removal of loading, the stress state has to be return its initial value resulting from preloads as σ_{pr}. But it does not return its exact initial value because of rounding errors and contact nonlinearity. When the difference between σ and σ_{pr} is too small, these errors cause relatively higher errors because they are scaled with time varying loads at the post process. In order to enlarge the difference between these two stresses, the magnitude of unit load is multiplied by 10000. This multiplication will be removed by dividing the matching time varying load at post process stage. An alternative approach is solving two analysis; one with only preload, other with only load including first analysis as initial condition. At the post process, the time dependent unit load is applied to finite element preload step result and it is the reason of mean stress in addition to time dependent load's mean values. The methodology of constructing time varying loads is explained before. Each of these time varying loads represents one event. Both Eurocycle and proving grounds consist of repeated events. These events represented by time series are combined at duty cycle processes by defining the repeats of each series. Here, these duty cycles are used as load data during fatigue analyses.

2.3. Fatigue Analysis

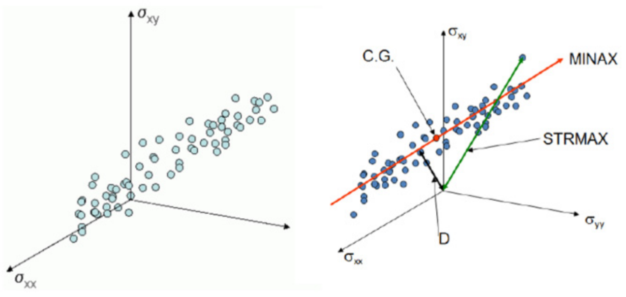
During post process, critical plane approach and signed tresca combination methods are both applied. At critical plane approach strain tensor is defined by the calculation of the most damaging plane simply by rotating the plane by ten degrees at each step and finding the most critical plane. The commercial software's algorithm for handling multiaxiality is basically explained. Stress history could be represented as a data cloud at Figure 6a. Shape and orientation of this data cloud could lead us to numerical values of the biaxiality and non-proportionality. The position of the center of gravity of the data cloud is determined and then principal moments of inertia I_1, I_2 and I_3 are The vector MINAX [5] corresponding to the principal axis with the minimum moment of inertia I_3 is obtained. STRMAX [5] represents the point with the largest distance from the origin. If the cloud of data correlates closely with a straight line through the origin as at Figure 6b, it can be stated as the loading is proportional.[5] The larger the aspect ratio of the cloud and/or its offset from the origin, the more non-proportional the loading.[5] The orientation of the vector MINAX states the average biaxiality. Non-proportionality factor is calculated as;[5]

$$NONPROP = \sqrt{\frac{I_3}{I_1} + \left(\frac{D}{2\,.STRMAX}\right)^2} \tag{8}$$

The components of MINAX (σ_{xx}, $\sigma_{yy,}$ $\sigma_{xy)}$ define a two dimensional stress tensor which has two principle stresses as σ_1 and σ_2. The mean Biaxiality ratio is calculated as;

$$BIAXIALITY = \sqrt{\frac{\sigma_2}{\sigma_1}} \tag{9}$$

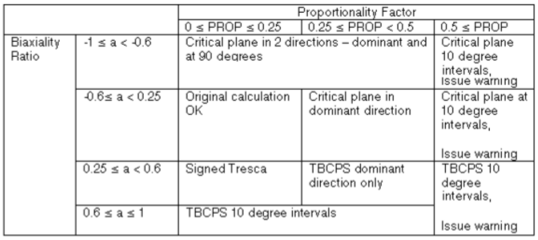
Absolute maximum principle strain could be defined as the principle strain with the largest magnitude. Signed Tresca criterion is selected with respect to biaxiality ratio (about 0.2-0.3 for all analyses) and non-proportionality factor (about 0.09 for all analyses). Therefore, Signed Tresca strain combination method is selected with respect to Figure 7. Other strain combination methods are also applied and about 30% difference is observed for a specific critical node.



(a) (b)

Figure 6: Multiaxiality at ncode Designlife [5]

Hoffman-Seeger method is used instead of Neuber plasticity correction to be able represent multiaxiality more accurately. Cyclic properties of material GGG45 is obtained from Ford material database. It should be noted that these material properties do not contain manufacturing effects as surface roughness, shot peening, cold or hot rolled. Calculations are based on strain-life method as a result of the probable occurrences of low cycle fatigue condition for cast materials.



		Proportionality Factor		
		0 ≤ PROP ≤ 0.25	0.25 ≤ PROP < 0.5	0.5 ≤ PROP
Biaxiality Ratio	-1 ≤ a < -0.6	Critical plane in 2 directions – dominant and at 90 degrees		Critical plane 10 degree intervals, Issue warning
	-0.6≤ a < 0.25	Original calculation OK	Critical plane in dominant direction	Critical plane at 10 degree intervals, Issue warning
	0.25 ≤ a < 0.6	Signed Tresca	TBCPS dominant direction only	TBCPS 10 degree intervals, Issue warning
	0.6 ≤ a ≤ 1	TBCPS 10 degree intervals		

Figure 7: Selection of strain combination method [5]

3. Conclusion

In the light of this methodology, different road load data can be exposed to the representative hub assembly model and comparisons are done. The main variables here that affect the damage results are the vehicle loading condition (vehicle types), suspension types and proving ground. Vehicle types are selected as road truck and tractor. Because of the loading distribution and loading transfer differences that comes from superstructure type, this discrimination has to be done. Suspension type also affected the loading transfer especially for the impact loading. Mechanical and air suspension is selected to show the variation. The last important criterion is the proving ground that the vehicle sign off is given for. Two different proving grounds are selected to fulfill the requirements of two different region's durability characteristics; South America and Europe. While running whole model with relevant data, critical hot spot nodes are selected and compared. The results of most critical node presented as pseudo-damage is illustrated at the Table 2. According to these results, drive axle is the most critical location for durability aspect. Pseudo-damages of front hubs are expected to be smaller because the existing hub design at the front is weaker with respect to stiffness and fatigue than the analysed design. The analysed design is actually a rear hub. So, it is expected that at this work front hubs have lower damage values. They are in 10^{-4} order as expected. The difference between loading condition shows a pseudo-damage difference between road truck and tractor. As expected, tractors have lower pseudo-damages. This indicates the status of their loading levels as tractors are exposed to lower loadings than 6x2 road trucks. Also suspension type is a contributor for the damage analysis and mechanical suspension system has higher damage results. Proving ground 2 (PG2), designed for South America, which has higher load levels, therefore higher damage results occur. Eurocycle load spectra represent 15990 kilometers while the proving grounds are approximately 7500 kilometers. The values at the Table 2 are relative damage values with respect to 7500 km. Eurocycle has relatively higher damage than proving ground 1 and lower damage than proving ground 2. For wheel sign-off, Eurocycle load spectra must consist of 258 cycles of 99 different loading amplitudes (98 events) representing 15990 km. Table 2 is used to determine that how many cycles are needed for hub designs with respect to Eurocycle load spectra.

Table 2: Relative pseudo-damage results of a critical node for all test tracks, axles and vehicles

Test Track	Tested Axle	Vehicle Type	Suspension Type	Damage	Equivalent Eurocycle test cycles
PG1	Front Axle	4x2 Tractor	Fr Mech - RR Air	1.13E-04	-
PG1	Drive Axle	4x2 Tractor	Fr Mech - RR Air	0.099	5561
PG2	Front Axle	4x2 Tractor	Fr Mech - RR Air	2.78E-03	-
PG2	Drive Axle	4x2 Tractor	Fr Mech - RR Air	3.14	175
PG1	Front Axle	6x2 Road Truck	Fr Mech - RR Air	3.21E-04	-
PG1	Drive Axle	6x2 Road Truck	Fr Mech - RR Air	0.1313	4193
PG1	Tag Axle	6x2 Road Truck	Fr Mech - RR Air	0.026	21175
PG1	Tag Axle	6x2 Road Truck	Fr Mech - RR Mech	0.65	847
Biaxial Test	-	-	-	2.134	258

It should be noted that front hub designs has much more damage than presented here, because the analyzed geometry is a rear hub which is more conservative than front hub. So, the equivalent EC test cycle column is left blank for front hubs. The spectra for hubs could be accelerated by determining the event based damage for 98 events of EC and then manipulating some of them. It can be done by simply changing the repeat numbers of events. As a result, stochastic road load characteristics and rotational stress variation on hub are considered to understand fatigue life of components and then representative load history for rotating components (Eurocycle and RLD) are modelled and compared to obtain pseudo-damage values to find equivalent standardized Eurocycle test cycles and in the light of this work, durability approval specifications of corner module parts could be commonized with finite element fatigue analysis.

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