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OPTIMIZATION OF HEAVY DUTY TRANSMISSION HOUSING USING VIRTUAL SIMULATION AND CORRELATED WITH PHYSICAL TESTS

Dharmveer
M.Tech Scholar, School of Engg. & Technology, SOLDHA HARYANA INDIA

ABSTRACT

In the current market trends there is always a need to arrive for light weight designs. For commercial vehicles, an attempt is made to re-design of existing cast iron transmission housing -considering its structural strength and stiffness. Advanced non-linear topology optimization methods have been addressed as the most promising techniques for light weight and performance design of powertrain housings.

Instead of conventional approach, a new finite element simulation approach has been adopted to align the project time plan (design and development time) to predict the stiffness and static factor of safety under defined VE commercial vehicles limited durability load cases.

For this, it was used non-linear topology optimization technique and it was experimentally verified. With this study, 20% weight reduction was achieved in transmission housing with the same overall structural stiffness – hence, same methodology can be implemented in other structural housing.

I. INTRODUCTION

The nature of commercial vehicle operation has always led the manufacturers to look for ways to reduce operational costs in order to maximize the profits for vehicle operators. The key factor that directly affects the profitability of commercial vehicle operation is fuel efficiency of a vehicle as it accounts for majority of the operational costs. The optimization of fuel efficiency can be achieved by weight reduction of vehicle components and sub-systems. Weight reduction also provides additional advantage as it is beneficial in loaded vehicle condition and unloaded condition. With the advent of FEA techniques and computer aided analysis it has become possible for the industry to explore complex component designs without exponential increase in developmental costs.

The powertrain consists of the engine and drive train (i.e., transmission, clutch, drive shafts, and drive axles). In HD commercial vehicles, the powertrain accounts for about 40% of the total weight. By increasing specific power density and optimization of designs, vehicle weight can be reduced. Opportunities for weight reduction in the drive train include lighter weight engines, transmissions and clutch housing [1].

For the HD commercial vehicles Powertrain component i.e. Transmission Housing, an attempt is made to replace heavy transmission assembly with an optimized design in order to take higher payloads and possess higher overall efficiency. For HD commercial vehicles, the observed engine torque range is around 600 Nm ~ 900 Nm; hence existing cast iron transmission housing has a 7 mm thick wall thickness with cross ribs around the housing.

In the current market trends there is always a need to arrive at designs that lower in weight & carry more pay load without compromising its strength bearing all the worst gear loads. Recent developments in material technologies have made aluminum a suitable replacement for light weight designs.However, the stiffness of aluminum is considerable lower than the cast iron material, this requires base thickness of aluminum design has to be increased by at least 30%. This implies existing design base thickness need to be increased from 7 mm to 9 mm, which will not at all commercially manufacturable for aluminum designs. And also, if we go for customized process for aluminum, the tooling cost increases by 40% ~ 50%. This is not viable, as it will directly impact on the vehicle cost. Additionally due to low volume sales in this platform, the time for return on investment is considerably high – which is not favorable to the customer.

Hence, it is decided that the existing cast iron design has to be optimized using CAE optimization techniques – with minimum changes in the existing tooling, without changes in the existing design envelop and compatibility of other mating components in the same vehicle platform.

To achieve same existing/proven cast iron housing stiffness for new housing stiffness with defined worst gear loading conditions, the existing cast iron housing has been analyzed first for defined worst gear loading conditions to know the stiffness at different known bearing locations. The idea was to come with new housing with the same stiffness arrived at the same locations as existing cast iron housing. Total 6 load cases have been analyzed to counter all gear loads with 36 responses using Altair OptiStruct software to meet the existing/proven cast iron design stiffness at the bearing locations. The stiffness values for the new optimized transmission housing are equivalent to that of existing proven cast iron transmission.

II. TOPOLOGY OPTIMIZATION

It is a mathematical approach that optimizes material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets. Using topology optimization, engineers can find the best concept design that meets the design requirements [2].

Topology optimization has been implemented through the use of finite element methods for the analysis, and optimization techniques based on the method of moving asymptotes, genetic algorithms, optimality criteria method, level sets, and topological derivatives.

Topology optimization is used at the concept level of the design process to arrive at a conceptual design proposal that is then fine-tuned for performance and manufacturability. This replaces time consuming and costly design iterations and hence reduces design development time and overall cost while improving design performance [3].

In some cases, proposals from a topology optimization, although optimal, may be expensive or infeasible to manufacture. These challenges can be overcome through the use of manufacturing constraints in the topology optimization problem formulation. Using manufacturing constraints, the optimization yields engineering designs that would satisfy practical manufacturing requirements. In some cases, additive manufacturing technologies are used to manufacture complex optimized shapes that would otherwise need manufacturing constraints.

III. PROCESS IMPLEMENTATION

First to make a design space without changing mating/interface parts and applied loads & boundary conditions in the concept design. Then stiffness of concept design has to compare to the existing/proven TM housing stiffness. This process continues till concept/optimized design stiffness is correlated with existing design stiffness using topology and size optimization. Final optimized design has to check for DFM (Design for manufacturing) and DFA (Design for assembly). This process of topology optimization is shown in the Figure 1.

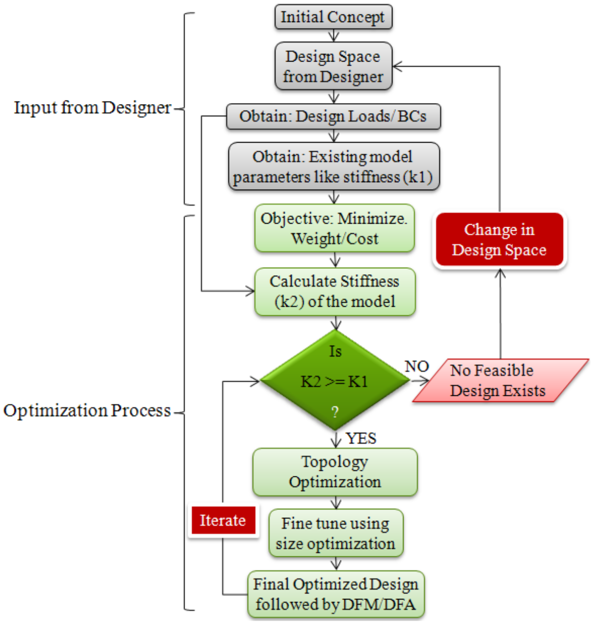
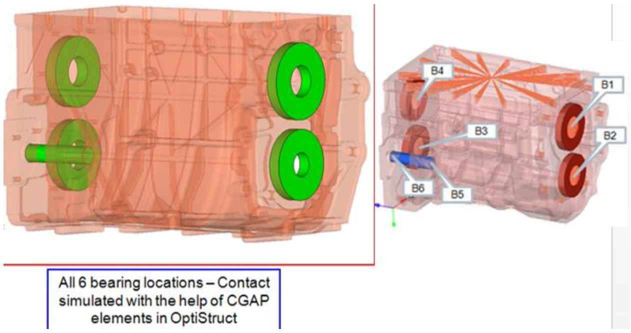


Fig. 1.Optimization – Process Implementation

IV. FE MODELLING

The geometry of the transmission housing is modeled in Pro-E, where the complete wireframe generated. The data is then translated to Initial Graphics Exchange Specification (IGES/STP) format and read into Hyper Mesh™, where the transmission housing is FE modeled by 3D Second order Tet mesh generation - using Tetra10 solid elements, i.e. 3D (2nd Order) tetrahedral elements with 10 nodes.

After meshing transmission housing, all bearings (2 counter shaft bearings, 2 main shaft bearings and 2 idler shaft bearings are meshed with the same element sizes and connected all bearings to the transmission housing with the help of PGAP elements, which will represents contact between the mating components, as shown in the Fig. 2.



All 6 bearing locations – Contact simulated with the help of CGAP elements in OptiStruct

Fig. 2.Transmission Housing - FE Model

Transmission Housing consists of 6 bearings, i.e. Input shaft (B1), Counter shafts (B2 & B3), Main shaft (B4) and Idler Shaft Bearings (B5 & B6).

V. PGAP ELEMENTS

Any model with non-linear CGAP (gap) elements uses the non-linear solution sequence. The element can be used for both static analysis and optimization; however, the assumptions of small displacement and small strain still apply.

Gap elements (CGAP) are defined node-to-node and require a property card and an orientation vector to be assigned to them. Gap element behavior is defined through the PGAP property card. Before creating a gap element, it is recommended to create the PGAP property card and then assign this property to the gap elements in the gaps panel (or other panels) in Hyper Mesh. Most of the panels that create 1-D elements (for example linear 1-D) can also be used to create gap elements by changing element configurations [4].

On the PGAP card (PGAP – Gap element property), the initial gap opening is defined by U0. The gap element offers very low stiffness until the gap is closed. Friction can also be specified, and gets activated once the gap is closed.

VI. ACTIVATING NON-LINEAR SOLUTION (NLPARM)

OptiStruct uses its linear solution sequence by default even if gap elements are present. A non-linear solution is activated for a sub case by including the NLPARM parameter. If NLPARM is not present in the sub case definition, the gap element has linear behavior. In this situation, the gap status is determined once at the beginning of the solution, and does not change as the solution progresses [4].

In HyperMesh, the NLPARM parameter can be defined by creating a load collector with card image "NLPARM." The NINC parameter on this card represents the number of equal subdivisions that the total load in a given sub case will be divided into. If NINC is blank, the entire load for a given sub case is applied at once. In most cases, this is the only parameter that needs to be defined. This NLPARM load collector needs to be included for the sub case along with static loads and SPCs.

VII. STRUCTURAL ANALYSIS

According to the applied loadings originating from different categories of mechanics, this non-linear elastic analytical procedure could further be divided into six load steps by means of the superposition principle for simulating various operating processes of the VECommercial vehicles Ltd – CAE standard powertrain load cases, a shown below:

1) 5.5g Vertical load + First gear loads
2) 5.5g Vertical load + Second gear loads
3) 5.5g Vertical load + Third gear loads
4) 5.5g Vertical load + First gear loads
5) 5.5g Vertical load + OD gear loads
6) 5.5g Vertical load + Reverse gear loads

Transmission housing assembly consists of all internal & external parts for CAE structural analysis (housing, upper case, gears, shafts, bearings, etc.), approx. 250 Kg.

The transmission housing is constrained at the front side and all gear loads are applied at the Input shaft (B1 @ front), Counter shafts (B2 @ front & B3 @ rear), Main shaft (B4 @ rear) and Idler Shaft Bearings (B5 @ front & B6 @ rear) locations, as shown in the Figure3.

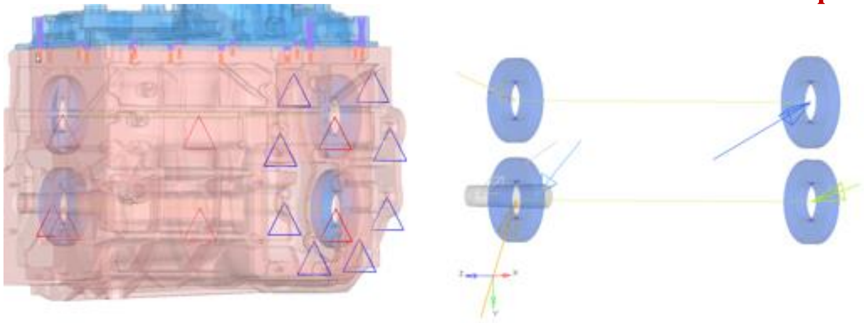


Fig. 3.Boundary Conditions

First, the existing cast iron housing has been analyzed for defined worst gear loading conditions to know about the stiffness at different known bearing locations, i.e. B1 to B6. The idea was to come with new housing design with the same stiffness arrived at the same locations as existing on the cast iron housing.

Total 6 load cases has been analyzed to counter all gearings with 36 responses using Altair OptiStruct to meet the existing/proven cast iron design stiffness at the bearing locations i.e. B1 to B6.

Figure 4 shows the design space for optimization. The wall thickness for design space is taken as 10 mm because existing design has a 7 mm thick with cross-over ribs.

The design iterations from Optimization of new transmission housing are shown in the Figure5a to 5d. After 8 iterations, the stiffness values are matched with existing design stiffness values at all 6 bearing locations.

Finally, we have checked the strength of Iteration 9 design, that is safe under all peak gear loading conditions and static factor of safetyis more than acceptable (FOS> 1.6) and is comparable with the existing transmission housing.

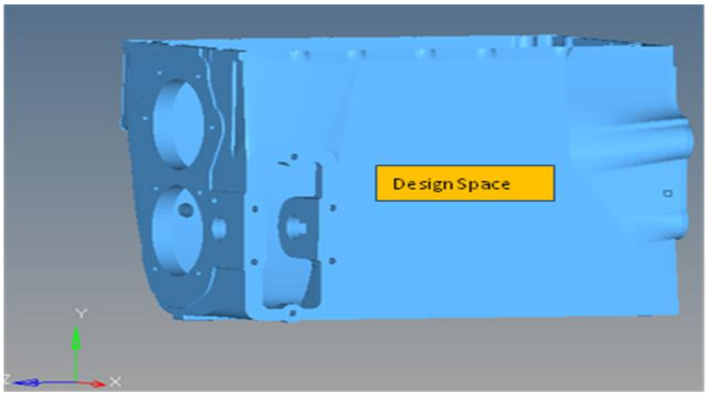
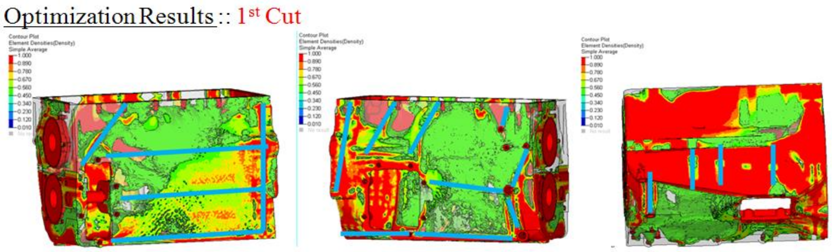


Fig. 4.Design space for optimization



Optimization Results :: 1st Cut

Fig. 5.a. Iteration 1Optimization results

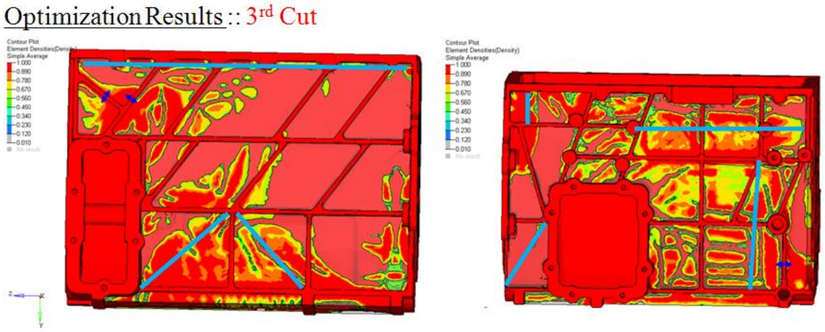
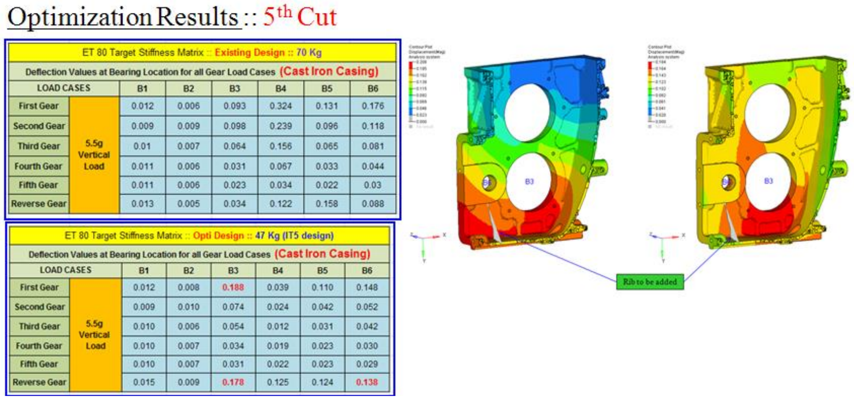

Optimization Results :: 3rd Cut

Fig. 5.b. Iteration 3 Optimization results


Optimization Results :: 5th Cut

ET 80 Target Stiffness Matrix :: Existing Design :: 70 Kg

Deflection Values at Bearing Location for all Gear Load Cases (Cast Iron Casing)

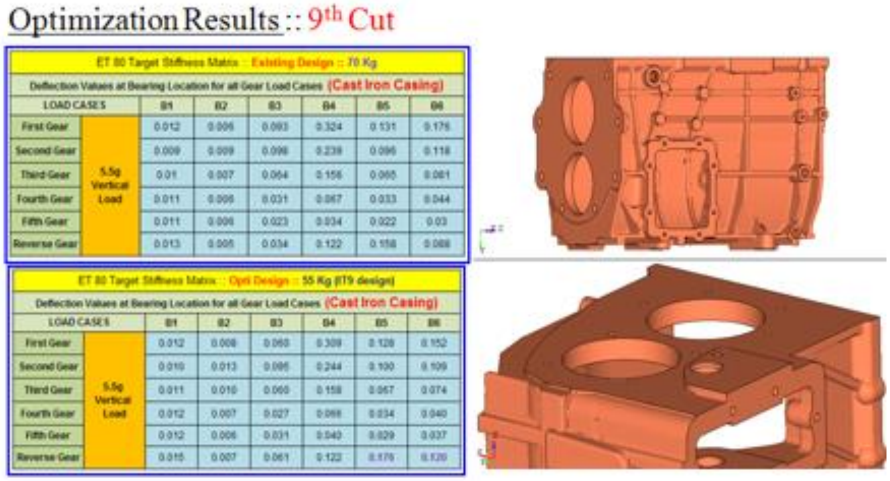
LOAD CASES		B1	B2	B3	B4	B5	B6
First Gear	5.5g Vertical Load	0.012	0.006	0.093	0.324	0.131	0.176
Second Gear		0.009	0.009	0.098	0.239	0.096	0.118
Third Gear		0.01	0.007	0.064	0.156	0.065	0.081
Fourth Gear		0.011	0.006	0.031	0.067	0.033	0.044
Fifth Gear		0.011	0.006	0.023	0.034	0.022	0.03
Reverse Gear		0.013	0.005	0.034	0.122	0.158	0.088

ET 80 Target Stiffness Matrix :: Opti Design :: 47 Kg (IT5 design)

Deflection Values at Bearing Location for all Gear Load Cases (Cast Iron Casing)

LOAD CASES		B1	B2	B3	B4	B5	B6
First Gear	5.5g Vertical Load	0.012	0.008	0.188	0.039	0.110	0.148
Second Gear		0.009	0.010	0.074	0.024	0.042	0.052
Third Gear		0.010	0.006	0.054	0.012	0.031	0.042
Fourth Gear		0.010	0.007	0.034	0.019	0.023	0.030
Fifth Gear		0.010	0.007	0.031	0.022	0.023	0.029
Reverse Gear		0.015	0.009	0.178	0.125	0.124	0.138

Fig. 5.c. Iteration 5 Optimization results (all deflections values are in mm)


Optimization Results :: 9th Cut

ET 80 Target Stiffness Matrix :: Existing Design :: 70 Kg

Deflection Values at Bearing Location for all Gear Load Cases (Cast Iron Casing)

LOAD CASES		B1	B2	B3	B4	B5	B6
First Gear	5.5g Vertical Load	0.012	0.006	0.093	0.324	0.131	0.176
Second Gear		0.009	0.009	0.098	0.239	0.096	0.118
Third Gear		0.01	0.007	0.064	0.156	0.065	0.081
Fourth Gear		0.011	0.006	0.031	0.067	0.033	0.044
Fifth Gear		0.011	0.006	0.023	0.034	0.022	0.03
Reverse Gear		0.013	0.005	0.034	0.122	0.158	0.088

ET 80 Target Stiffness Matrix :: Opti Design :: 55 Kg (IT9 design)

Deflection Values at Bearing Location for all Gear Load Cases (Cast Iron Casing)

LOAD CASES		B1	B2	B3	B4	B5	B6
First Gear	5.5g Vertical Load	0.012	0.008	0.060	0.309	0.128	0.152
Second Gear		0.010	0.013	0.086	0.244	0.100	0.109
Third Gear		0.011	0.010	0.060	0.158	0.067	0.074
Fourth Gear		0.012	0.007	0.027	0.068	0.034	0.040
Fifth Gear		0.012	0.006	0.031	0.040	0.029	0.037
Reverse Gear		0.015	0.007	0.061	0.122	0.176	0.120

Fig. 5.d. Iteration 9 Optimization results (all deflections values are in mm)

VIII. STATIC ANALYSIS RESULTS

Figure6 shows the stress plots for both existing design and Optimized design under worst load case i.e. 5.5g Vertical Load + Reverse Gear Loads. Both static results are almost same with 15 KG weight saving.

Table 1 shows, the comparative (Existing design and Optimized design) results summary for all 6 load cases. The static FOS are lower than the acceptable FOS 1.0.

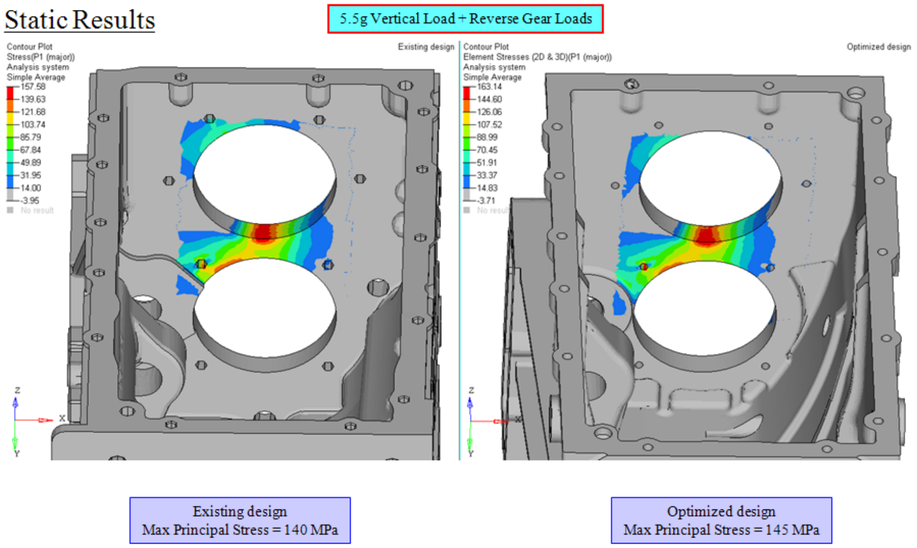


Fig. 6.Static analysis results

Table 1.Static analysis results summary

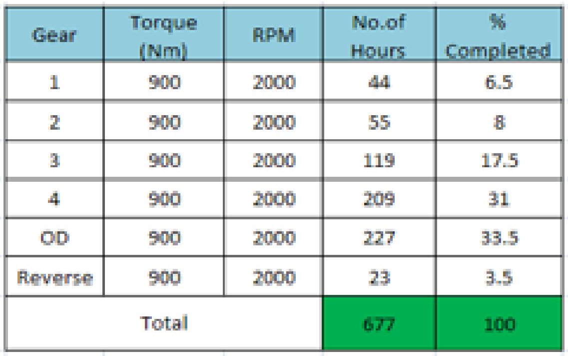
LOAD CASES		Existing design (70 Kg)		Optimized design (55 Kg)		Accept. FOS
		Max Principal Stress (Mpa)	FOS @ SG400	Max Principal Stress (Mpa)	FOS @ SG400	
First Gear	5.5g Vertical Load	88	1.82	97	1.65	1.0
Second Gear		49	3.27	53	3.02	1.0
Third Gear		31	5.16	34	4.71	1.0
Fourth Gear		14	11.43	15	10.67	1.0
Fifth Gear		8	20.00	8	20.00	1.0
Reverse Gear		140	1.14	145	1.10	1.0

IX. EXPERIMENTAL VERIFICATION

As per VE Commercial Vehicles Ltd, standard durability rig has been setup as shown in the Figure7 and then tested the Optimized transmission assembly in which TM housing is the test component. TM housing at each gear for maximum torque condition has been evaluated with defined duty cycles (Torque 900 Nm, 2000 RPM) as shown in the below Table 2. This Optimized TM design has completed the entire duty cycles without any failures and passed the durability testing cycle.

Fig. 7.TM housing-rig setup

Table 2.TM housing - Duty cycles



Gear	Torque (Nm)	RPM	No.of Hours	% Completed
1	900	2000	44	6.5
2	900	2000	55	8
3	900	2000	119	17.5
4	900	2000	209	31
OD	900	2000	227	33.5
Reverse	900	2000	23	3.5
Total			677	100

As per VE Commercial Vehicles Ltd, standard endurance test cycle has been carried out on 3 vehicles for 180000 km each. Therefore a cumulative of 540000 km has been covered on the vehicle without any failure. Hence vehicle validation has been concluded and certified as OK for implementation on regular vehicles [5].

X. CONCLUSIONS

- Using the proposed cast iron transmission housing in our organization –
    - ➢ It is estimated that cost savings is of up to 10%
    - ➢ Reduction in weight is by 15 Kg (20%)
- Almost 90% correlation achieved with Strain test data and CAE simulation tool.
- Topology Optimization process can be implemented for all existing costlier CI parts – To reduce cost & overall weight of the vehicle.
- An accurate FE simulation methodology is established to reduce the product development time & cost of the design - To align the project time plan and to ensure First Time Right at the development phase.
- Time saving in product development with respect of new transmission housing design – Which improves the product performance, reliability and durability.