Deliverable 2.2

SYS2WHEEL In-Wheel System

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Lead Beneficiary	ELAPHE
Deliverable Type[1]	R
Dissemination Level[2]	PU
Due Date	30. June 2020
Pages	37
Version	3.1
Project Acronym	SYS2WHEEL
Project Title	Integrated components, systems and architectures for efficient adaption and conversion of commercial vehicle platforms to 3rd generation BEVs for future CO2-free city logistics
Project ID	824244
Project Coordinator	VIRTUAL VEHICLE Research Center (ViF) Bernhard Brandstätter (bernhard.brandstaetter@v2c2.at)

SYS2WHEEL has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824244.

[1] Report (R), Prototype (P), Demonstrator (D), Other (O)

[2] Public (PU), Restricted to group (RE) or programme (PP), Consortium (CO)

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Version Log

Rev #	Date	Author / Company short	Description
1	1.4.2020	Krstan	ELAPHE
2	5.6.2020	Biček	ELAPHE
3	3. 7. 2020	Bernhard Brandstätter	ViF
4	9.7.2020	Biček	Modifications requested by Sunay Güler (Tofas after review)
5	29. 7. 2020	Bernhard Brandstätter (ViF)	Final corrections, disclaimer and coordinator approval
6	2. 9. 2020	Matej Bicek	Blurred image exchanged

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1 Summary of the Targeted System

- The Fiat Doblo Maxi vehicle which is shown in figure 1, is used for whole project package.
- The existing solution consists of 2 x M700 in-wheel electric motor on front wheels and 2 x in-wheel suspension on rear wheels.
- The drivability and braking system features are completely proper with EU Homologations.

Figure 1: Fiat Doblo Maxi

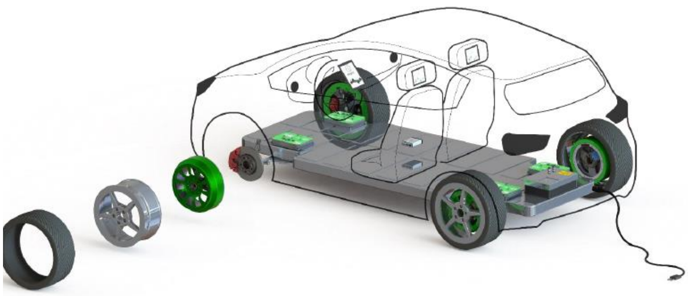


Figure 2: in-wheel motors in the front and in-wheel suspension in the rear, enabling increased space for cargo or battery

2 Development and Integration of the In-Wheel System

The modelling for the Fiat Doblo Cargo electric was not so challenging since the vehicle is electric in its origin. Modifications will be required, mainly in corners where attachment points and rim adaptions for in-wheel motor and in-wheel suspension system. This is required since it impact on the full vehicle design and dynamics. Power electronics will be integrated in the vehicle model and all this will be a starting point for the thermal analysis in task 2.6.

The highly energy efficient electric in-wheel propulsion was updated for the needs of Fiat Doblo and the project scope. The system will consist of two M700 motors (universal), two inverters, one PCU, disc brake and in-wheel suspension. In addition to the space limitations the goal of the motor design is to reduce the amount of rare Earth magnetic material. By optimizing the design and by partially substituting them with lower grade magnet material and by partial use of reluctance torque the expected decrease is up to 35%.

REE has together with its partners spearhead the development of an in-wheel suspension system with the goals of saving vehicle space and footprint, making rear wheel weight sprung all while maintaining high performance and comfort for passengers and cargo. REE's scope will entail all connections between chassis/steering system and wheels including mounts, suspension arms, springs/dampers, bushings and torque transferring devices from motor to wheel, all designed according to requirements and total vehicle architecture.

The integration of the hardware, software adaptations, definition and adaptations of interfaces to the PCU, harmonization of inverters, electronics and energy storage components was carried out before the final integration and commissioning. The second focus of this task is responsible for the functional testing of the In-Wheel system to be ready for the integration in WP5. The following functional or short durability tests will be done on power Electronics, in-wheel-motors, testing of the wheel with integrated IWM and suspension, Functional and basic durability testing of in-wheel system and fine tuning of the electric in-wheel powertrain design for the integration on the demonstrator in WP5.

2.1 Modularity of the In-Wheel motor

The in-wheel motor intrinsically offers very high modularity for similar vehicle sizes. The important part when targeting modularity is which vehicles should the motor cover. The first step in calculating IWM’s parameters is the calculation of vehicle’s requirements from basic laws of physics. Vehicle parameters such as mass, dimensions, air drag and rolling resistance coefficients have to be coupled with expected driving demands such as maximum speed, hill climbing ability and acceleration. This analysis results in the required input parameters or boundary conditions, which are a starting point of propulsion and motor design and one of the most important aspects of designing the propulsion.

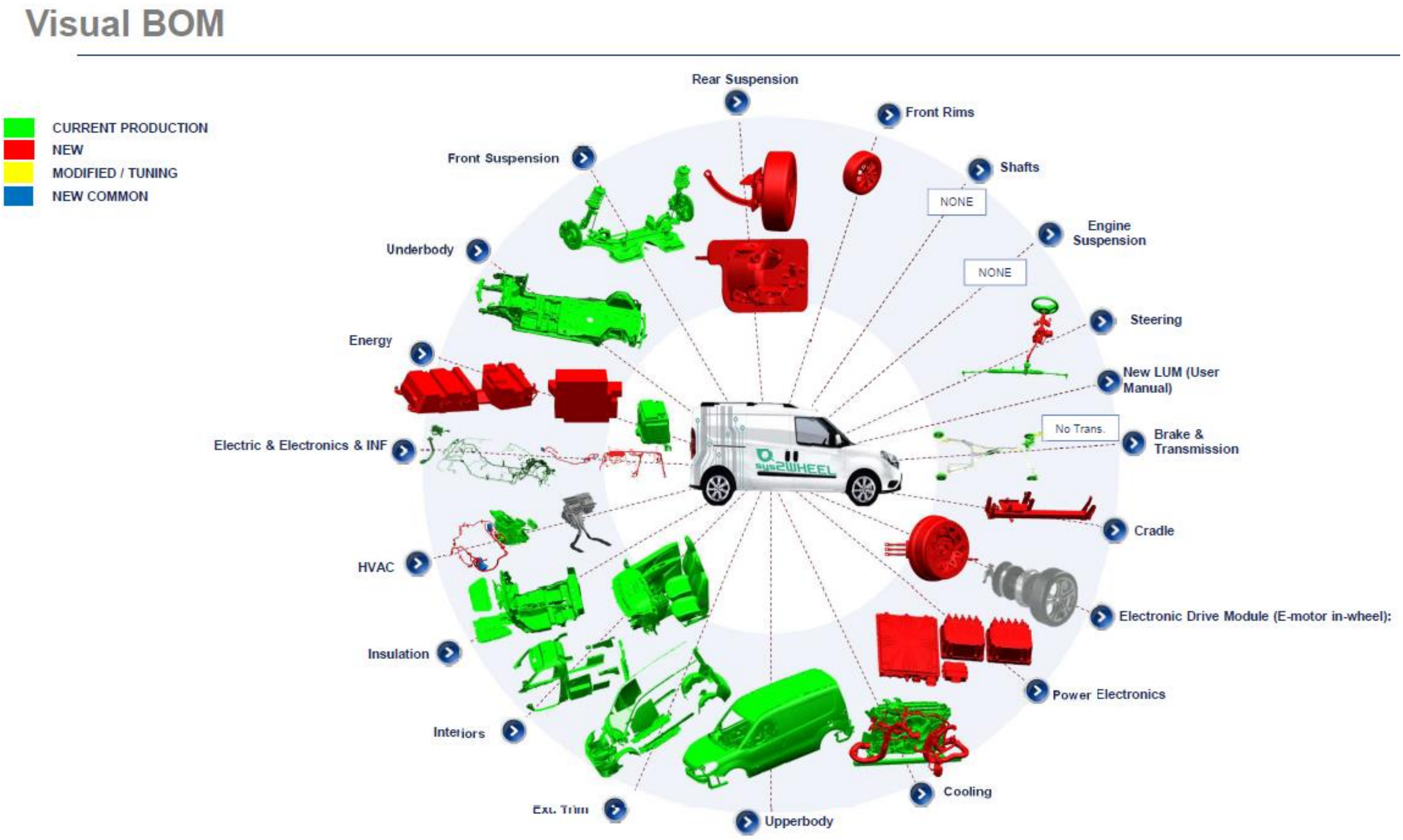
Propulsion parameters such as power, torque, efficiency, weight, size, etc. – depend on vehicle data and expected driving performances. In order to get the right performance, Elaphe is supported by computer simulations and flexible development process, based on:

> Vehicle data (weight, air drag data, friction data, energy source characteristics, number of motors, rolling radius, frontal area etc.)

> Typical use of the vehicle (driving cycle, top speed, expected range, demanded hill-climbing abilities etc.)

2.2 Reduction of complexity and manufacturing cost

The complete BOM of changed parts is shown by the OEM below:



Conventional mobility with Internal Combustion Engines (ICE) and complex drivetrains as shown on Fig. 1 is facing competition with electric vehicles within the passenger car market and lately also within commercial automotive segments. Showcasing electric vehicles is a thing of the past as they are pushed by incentives and national or associative directives to being frequently driven on global roads.

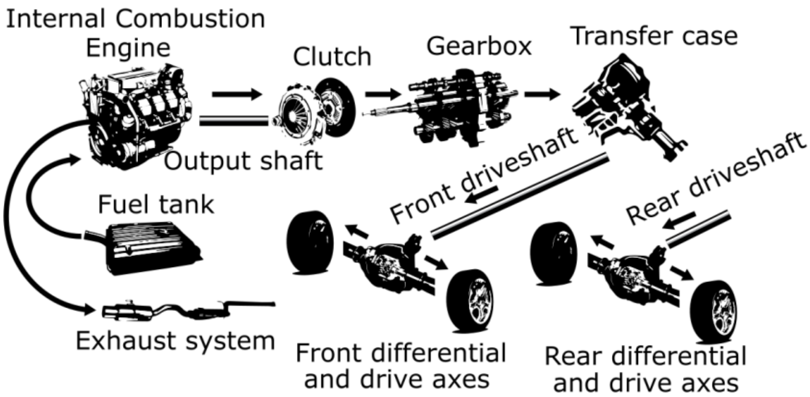


Fig. 1. ICE drivetrain with an all-wheel drive with obvious complexity [1].

In-Wheel Motor (IWM) propulsion platforms (Fig. 2) intrinsically allow larger design space, lowering the centre of gravity and reduction of required parts for any vehicle [2], [3] and consequentially offer cost reduction potential [4], [5]. Higher energy efficiency and increased range [6]–[8] are met as no mechanical transmission is required and the wheels are propelled directly, without the reduction of speed and increase of torque [9], [10].

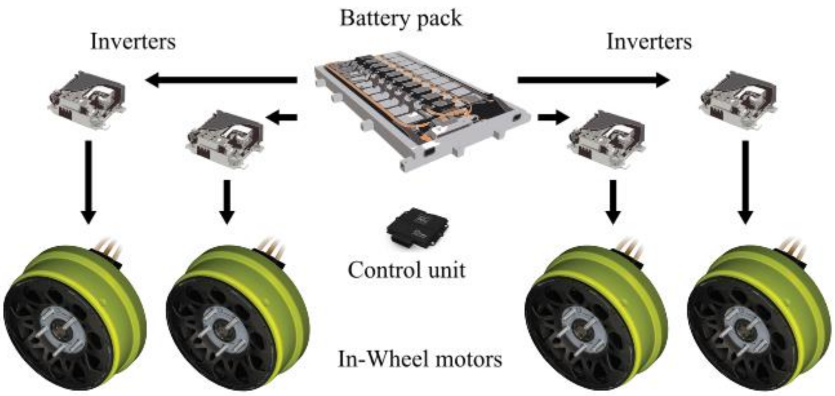


Fig. 2. IWM propulsion platform with Elaphe M700 all-wheel drive showing simplicity [1].

More space for passengers and cargo [10]–[13] allow vehicle architects to utterly change the way cars look and perform (**Fehler! Verweisquelle konnte nicht gefunden werden.**) [14], [15] with components not needing fixed mechanical coupling.

2.2.1 Conventional production techniques for IWM components enabling low production costs

Design of the most common Permanent Magnet Synchronous Motor (PMSM) for in-wheel motor application has an outer rotor with a relatively small air gap between rotor and stator [8]. In relation to the geometry, components under the evaluation are larger Al and steel parts. These cover Rotor,

Rotor plate and Stator (Fig. 3). A common geometrical property for cost driver components is high diameter and low wall thickness.

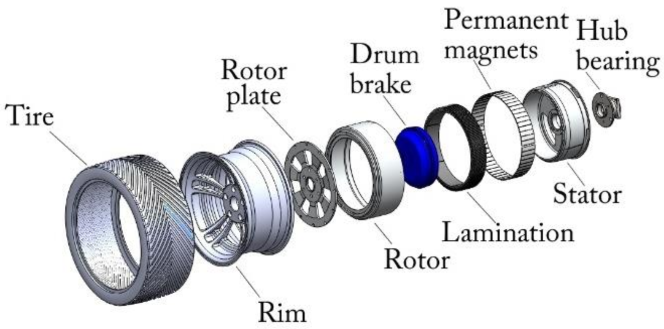


Fig. 3: Typical IWM with rim and tire layout with outer rotor in explosion view [1].

Since IWMs achieve high mechanical power outputs ranging also above 110kW [34], large amount of heat is generated. With the objective of increased heat dissipation, active cooling is required for stator housing. In relation to general functional requirements, several exist in relation to housing components:

- electromagnetic compatibility
- structural integrity
- environmental endurance
- acoustic emission

Within structural integrity point, a detailed understanding of possible elastic deformation of housing is required. On a primary level, the loads acting on an in-wheel motor can be divided based on their origin. Internal loads originate from the motor itself while external loads are acting on the motor from the outside [29]. After knowing the worst-case load scenarios and performing numerical simulations for stress-strain relation, additional functional analyses are required to assess the required tolerance field of each component. With performed tolerance stack analysis an iterative loop defines the maximum International Tolerance (IT) grade for each component dimension. These are targeted to the highest allowable values in order to meet as robust production processes as possible and cut costs.

IWM’s Key Performance Indicator (KPI) is the air-gap between rotor and stator, which is normally on a high diameter with 300-450mm in diameter and ranging from 0,3-2 mm [8]. This is taken into account when performing numerical simulations for assessing housing’s structural integrity. Each machining process should be reviewed for its accuracy limitations. The objective should be set for as less manipulation as possible and utilization of equipment with high process stability and productivity. Based on [30], it is evident that conventional CNC machining equipment can be used to target IT7, being also the most demanding requirement for dimensional tolerancing. Geometrical tolerancing should be defined based on tolerance envelope size and functional requirements related to motor application and geometry. In general, specific high diameter and thin wall geometry require geometrical tolerances for cylindricity, tolerance of position, total runout with values above 0,10 mm.

Most spread production processes covering high stability and automotive series, applicable for IWM components are:

- High Pressure Die Casting (HPDC) - stators
- Deep drawing with modular tools - rotors

- High speed CNC turning – stators and rotors
- 2 spindle 4-axis CNC milling - stators

Each of the mentioned production processes has several steps to deliver the workpiece to the final stage. Fig. 4 shows the first six casting steps for stators:

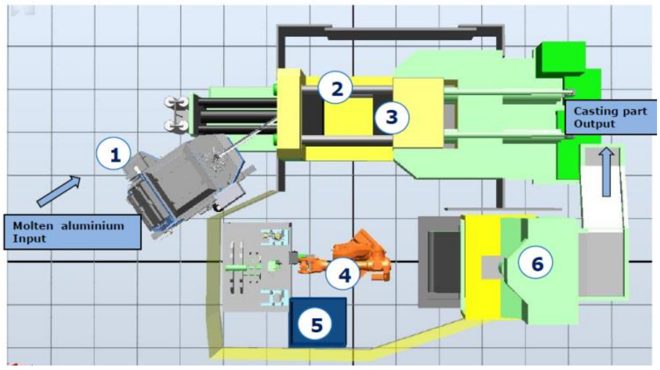


Fig. 4: Example of HPDC process with: 1. Furnace, 2. Die Casting machine, 3. Spraying head, 4. Robot, 5. Cooling chamber, 6. Trimming machine [1].

In addition to the mentioned, castings steps cover also: X-ray part revision, shot blasting, tempering, CNC machining, washing, impregnation, leakage testing, surface treatment and final control with packaging.

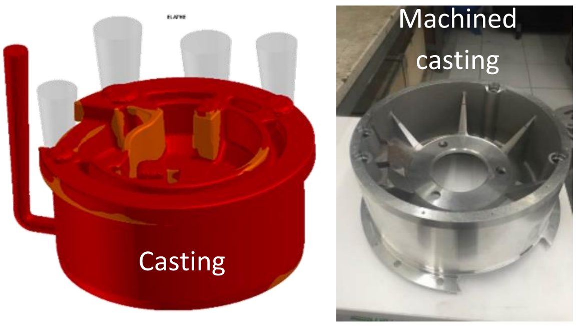


Fig. 5: Al casting of stator for IWM application

IWM rotor components can be produced from sheet metal or bulk material by cold or hot forming. Since the currently applied deep drawing process delivers the part diameters in IT11 to IT13 range, the subsequent machining to the final part's shape is indispensable. However, the machining operations can be also drastically shortened through the forming by ironing and calibration processes of the part applied after the deep drawing operation. With these processes the diameters with dimensional IT range from IT7 to IT9, however the tooling costs are increased. Once the deep drawing operation is selected for production of IWM components, it is necessary to consider the technology-oriented design of produced parts and use the advantages of this technology in comparison to other manufacturing concepts.

2.3 e-motor cost reduction

In-wheel motors are integrated in the front wheels are replacing the ICE propulsion. The comparison should cover packaging space, torque requirements, speed requirements, weight of the complete system, integration complexity, durability, dynamic options and safety aspects. Each OEM estimates these propulsion system properties differently, very related also with the application that is targeted. The general objective of Sy2Wheel project is to offer a mature solution enabling OEMs retrofitting of existing vehicles. With this in mind, the first property – Packaging space is the most persuasive as shown below:

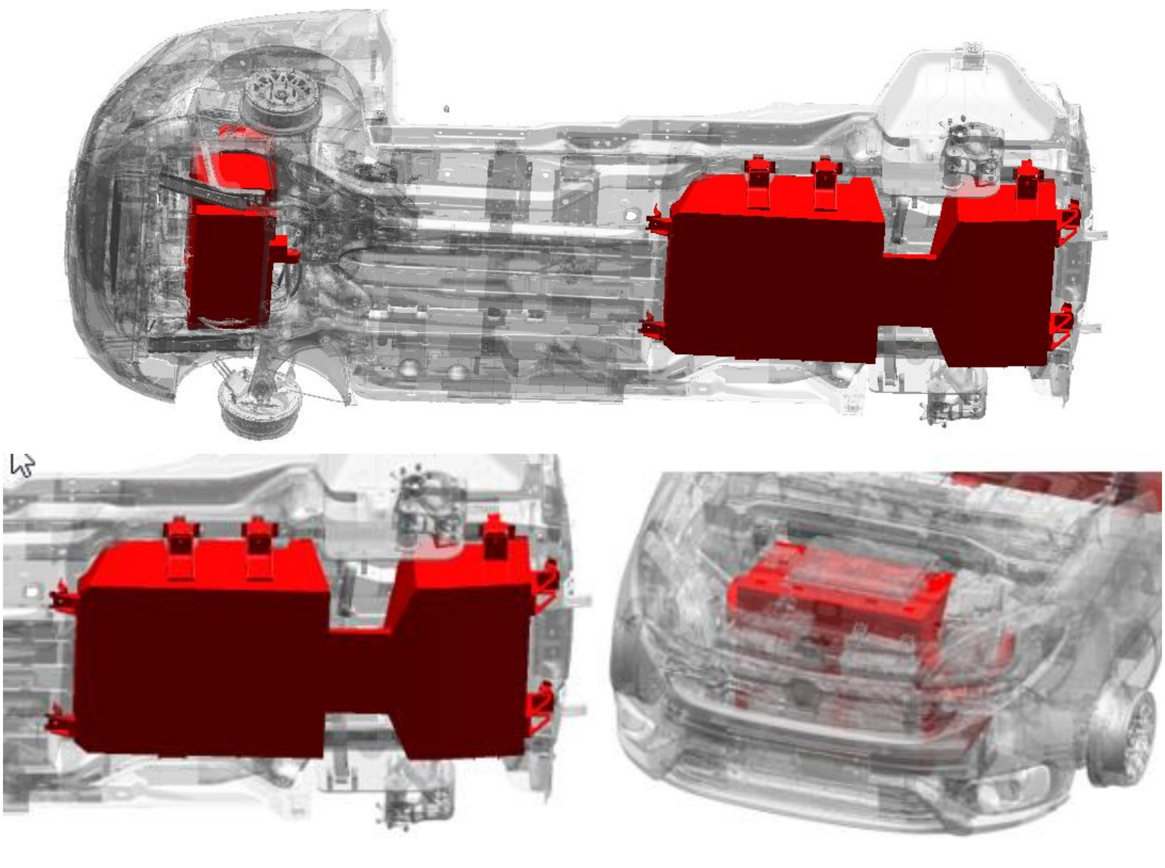


Figure 3: Red colour represent the reserved sapce for the battery

Picture clearly shows there is a lot of space for cargo and/or energy source, which is not achieved by other technologies in such an extent.

3 M700 motor modifications

To guarantee required high efficiency of the in-wheel motor with reduced amount of rare Earth magnetic material and provide functional safety of whole vehicle, standard M700 motor was modified in following segments:

- ABS sensor integration
- Electromagnetically active parts redesigned

3.1 ABS sensor integration

To achieve functional safety of the vehicle, Fiat Doblo front ABS sensor was integrated in the M700 in-wheel motor. Sensor is equipped with ABS chip OH191/E. Basic information of sensor are that, it doesn’t have active pulse, latches previous signal, it changes level on zero cross and it has two states, low and high.

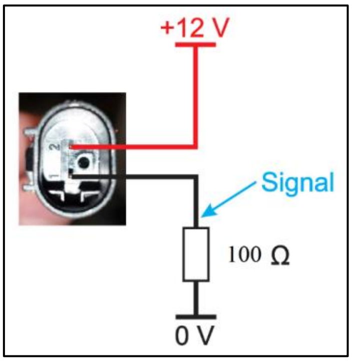


Figure 4: ABS sensor connection

M700 motor is designed around hub bearing VKBA 3634 (VW group hub bearing) and compatibility with integrated magnetic ring was tested. It was identified that sensor shall be maximum 2,60mm away from magnetic ring on hub bearing.

Virtual integration of ABS sensor was made with 2,45 mm of gap between magnetic ring and ABS sensor to overcome manufacturing and installation tolerances of adapters and modification of in-wheel motor.

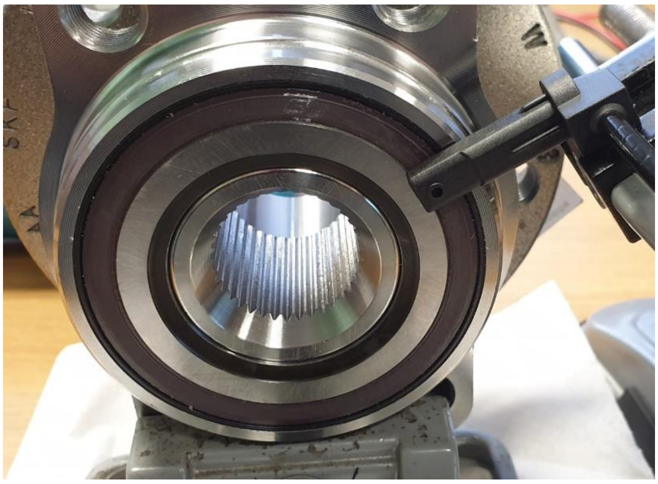


Figure 5: Fiat Doblo ABS sensor and hub bearing VKBA 3634

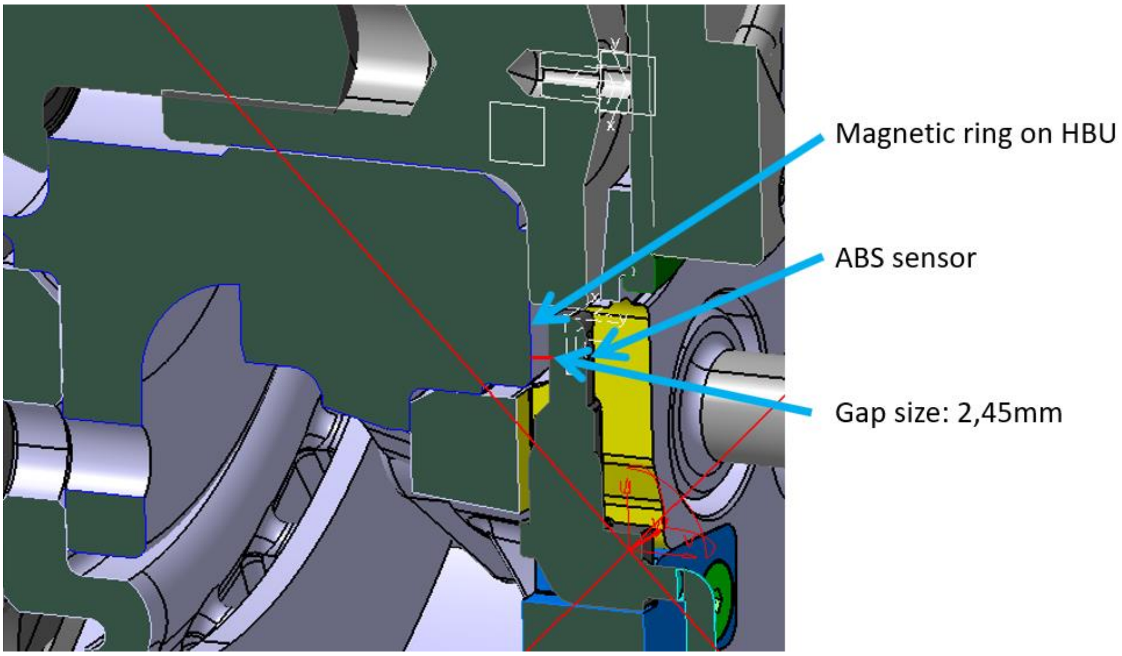


Figure 6: Virtual integration of ABS sensor in the IWM with 2,45mm of clearance to compromise manufacturing and installation tolerances.

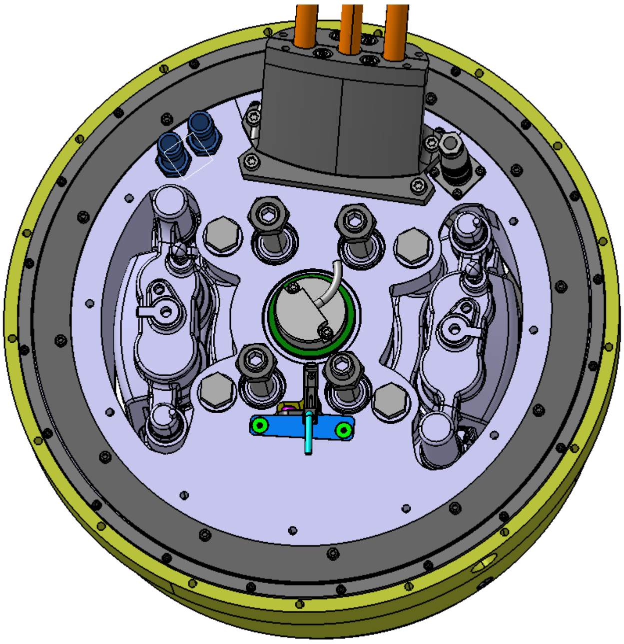


Figure 7: ABS sensor integrated in the M700 In-Wheel motor

ABS sensor is meant to be bolted to the vehicle's knuckle in radial direction, which is not possible when integrated in the stator of in-wheel motor. Therefore, an additional adapter was designed which is carrying ABS sensor. This layout enables mounting of ABS sensor in axial direction by using 2x countersunk bolts. To do so, modification of stator housing is necessary to provide pocket for ABS sensor and adapter and two threaded holes for fixation. Modification is made on a CNC milling machine.

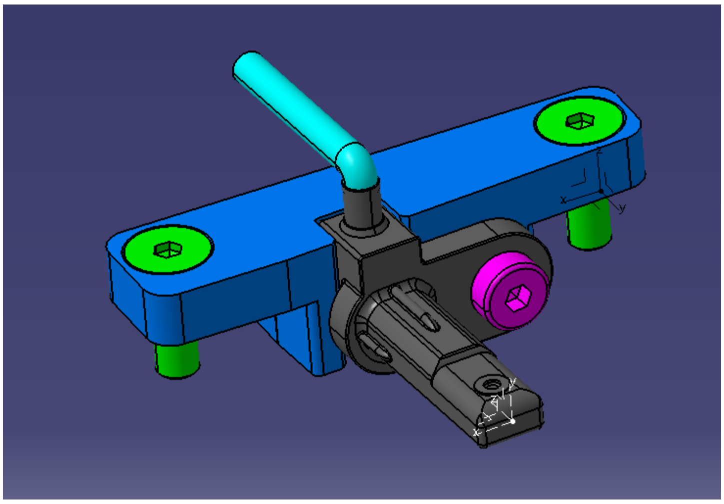


Figure 8: ABS sensor mounted on adapter

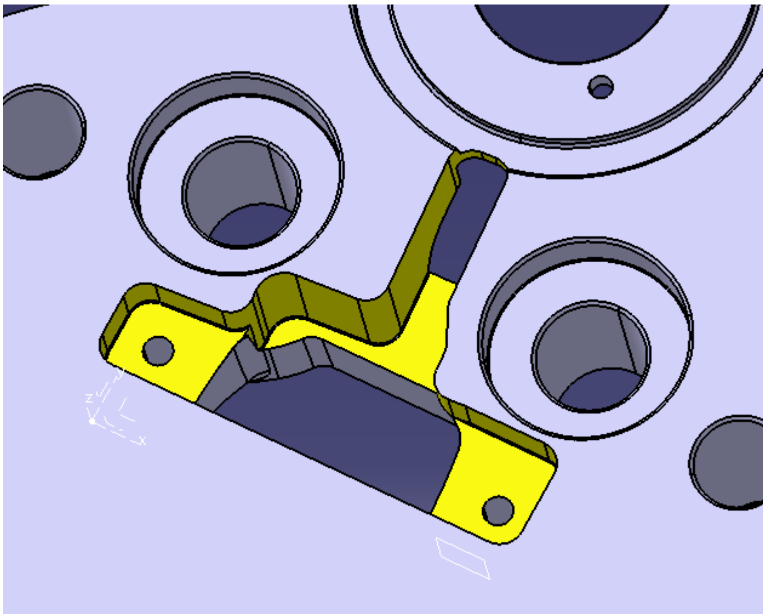


Figure 9: Modification of stator housing to integrate ABS sensor.

In Fig. 8 the energy harvesting device is shown. The Harvester supplies the in-wheel sensors that are used for control purposes and have to be supplied continuously with energy.

Figure 10: In-Wheel Sensors and location for the energy harvesting device (white)

3.2 Active part redesign

To achieve better efficiency, we redesigned the whole electromagnetically active part of our motor. We changed the wire geometry to get a much better fill-factor. For this change to be possible, we had to change the bladestack geometry, which in turn requires a change on magnet geometry.

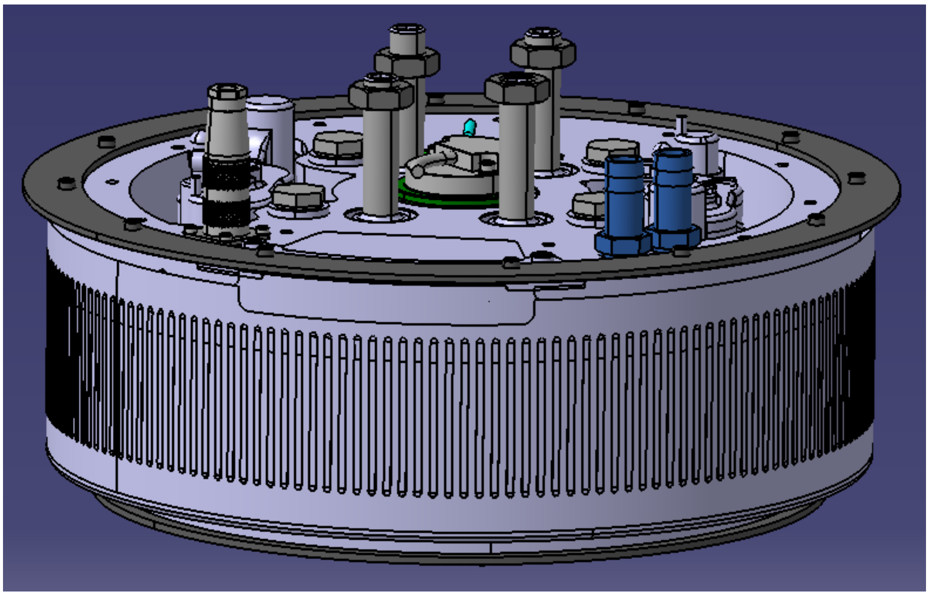


Figure 11 Redesigned stator subassembly

The redesigned parts have an impact on the performance of the motor so all the electro-magnetic calculations were done again and from the results, the new geometry of all the parts was defined.

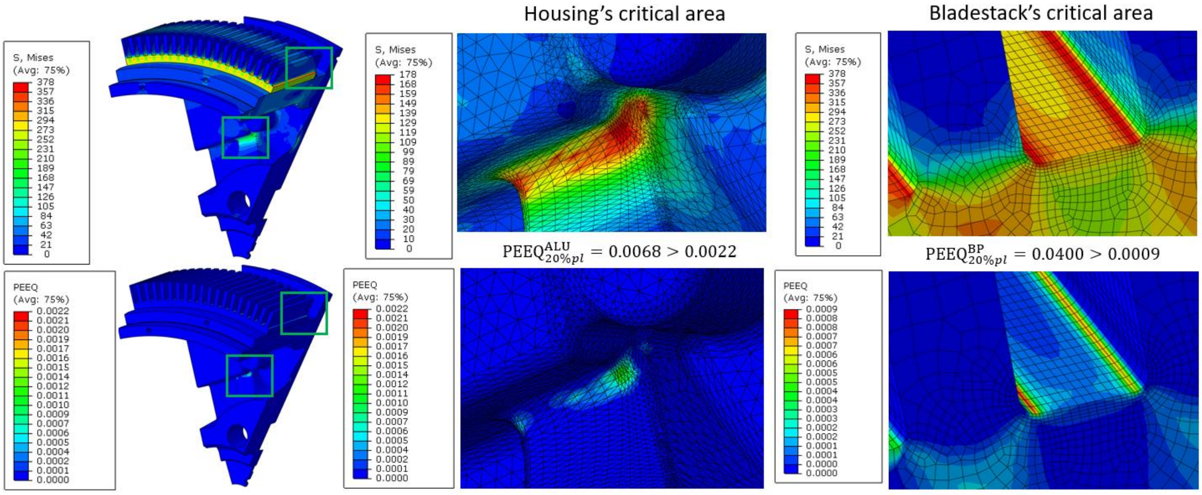


Figure 12 Results of the structural integrity simulation

We could say that the bladestack was completely redesigned. The geometry of the slots has changed, so we had to make a new tool for cutting the metal sheets and assembling the bladestacks with our suppliers. We also had to make modifications on some of our assembly tools since the features which were changed, were also used as positioning features on them.

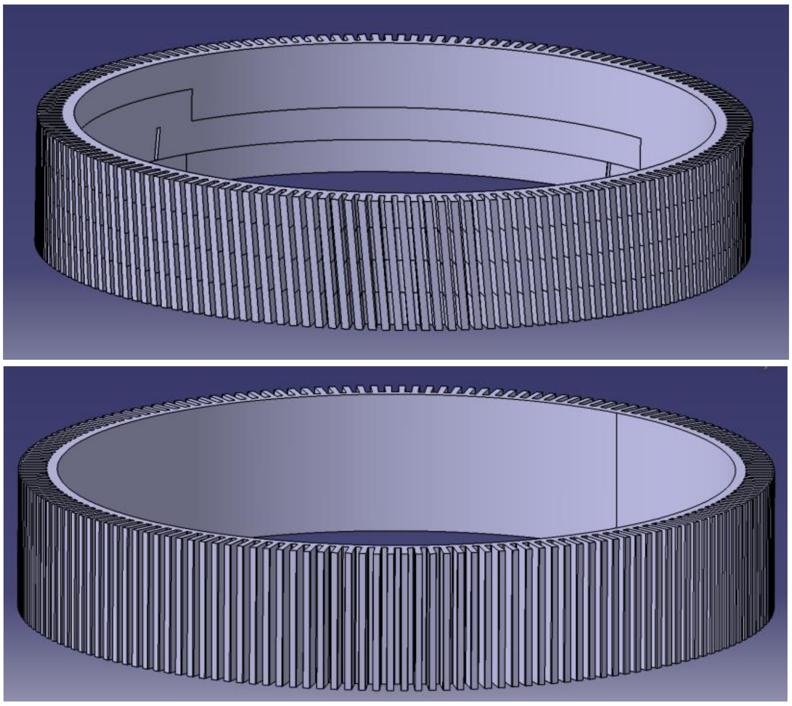
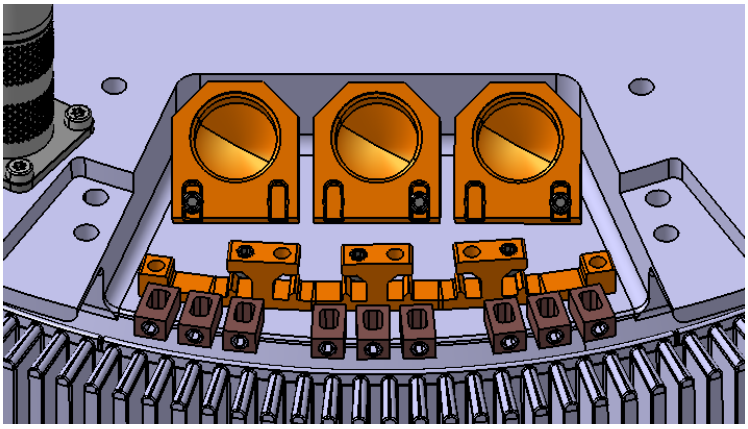


Figure 13 Old version of the bladestack on top and the new one below it with changed skewing parameters

To connect the wires, we bolt them together on machined copper parts. This parts also had to be redesigned because of the new wire geometry. Wires also have to be connected to the three phase cables. This if the main function of the phase connectors. Similar connectors were used on an older type of motor which we produce. But because of different wire geometry, the parts had to be redesigned. They also have to be accurately positioned on the motor. Their alignment with the phase cables must be perfect. We achieve this position with a positioning tool which we were able to reuse from an older project with some minor modifications.



The implementation of all these changes on physical components was the more difficult part of the project. We basically had to reengineer the entire manufacturing and assembly process of the main parts of the motor. This includes 5 of the most critical and complex assembly steps, which require specific machines and tools to be done. As this are very delicate operations where the smallest mistake leads to the failure of the motor, extensive testing on many prototyped parts was required to exactly determine each step of the new assembly process. Two of the machines had to be modified for use with new motor components. One was completely redesigned and manufactured but is still working on the same principle, and one was developed and made from bottom up. For the later, we had to change the basic concept on which it operates.

The new geometry of the magnets is more complex due to the NVH and reduced cogging torque related requirements. Since their geometry was changed, also the tool for positioning and gluing the magnets to the rotor had to be redesigned, made and tested.

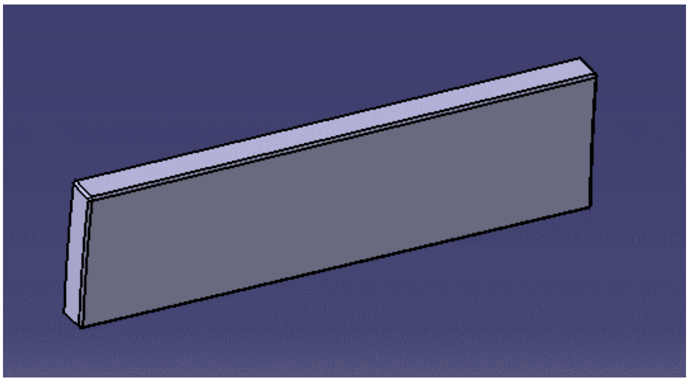


Figure 14 The new, skewed geometry of the magnet

The position of the magnets is very important and can have a big impact on motor performance and NVH. The tool to perform the operation of positioning the magnets, has to be as precise enough to fulfil positioning requirements. Like the magnets also the manual assembly tool has a complex shape which makes it even more difficult to manufacture it with sufficient accuracy. In series production this positioning should have the same complexity as tools for conventional magnet placement. The rotor design has a patentable solution and will for confidentiality reasons not be shown.

Another important process is getting the wire ready for assembly. Elaphe has a machine, which was developed specifically for this task. Due to the geometry changes, it had to undergo significant modifications through several iterations to get the desired result with the new wire geometry.

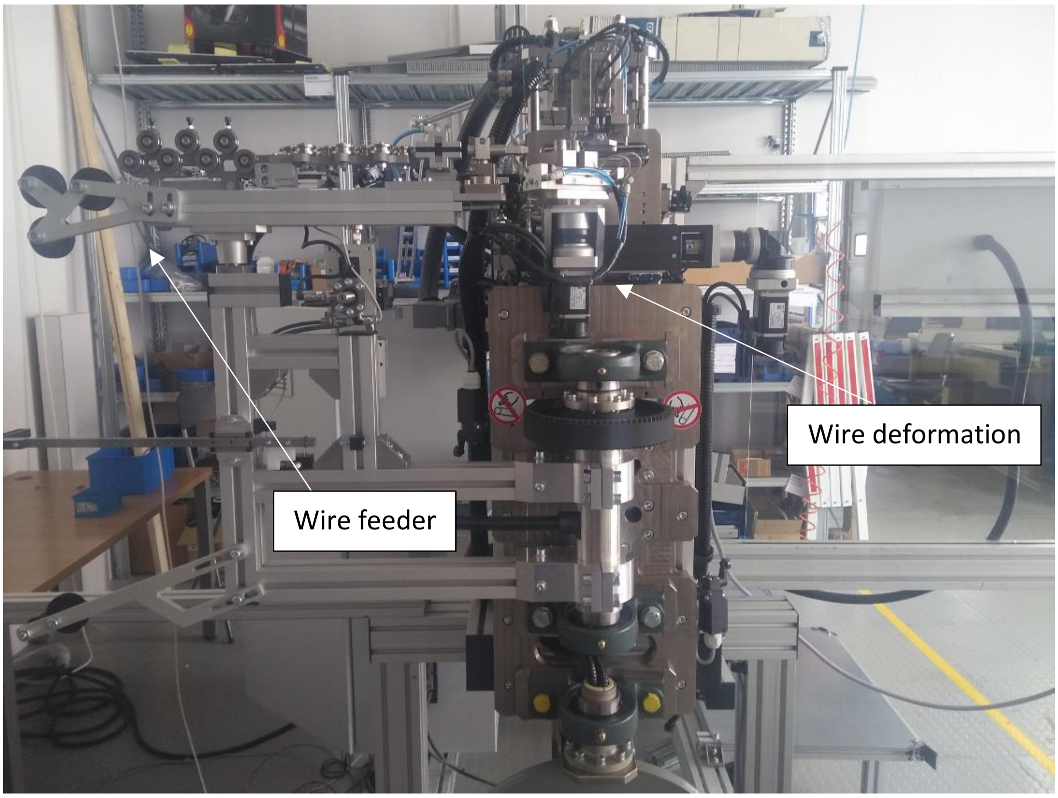


Figure 15 Customized wire deformation tool.

We also had to resolve wire insulation challenges which took quite some time and effort. On some first tries, the insulation breakdown was common. Our experienced colleagues were able to solve this problem with our state-of-the-art equipment and some ingenuity. After several iterations to the process and tools, the breakdowns are now eliminated. We can also detect this kind of failures in time and have defined corrective actions and procedures in case they happen.

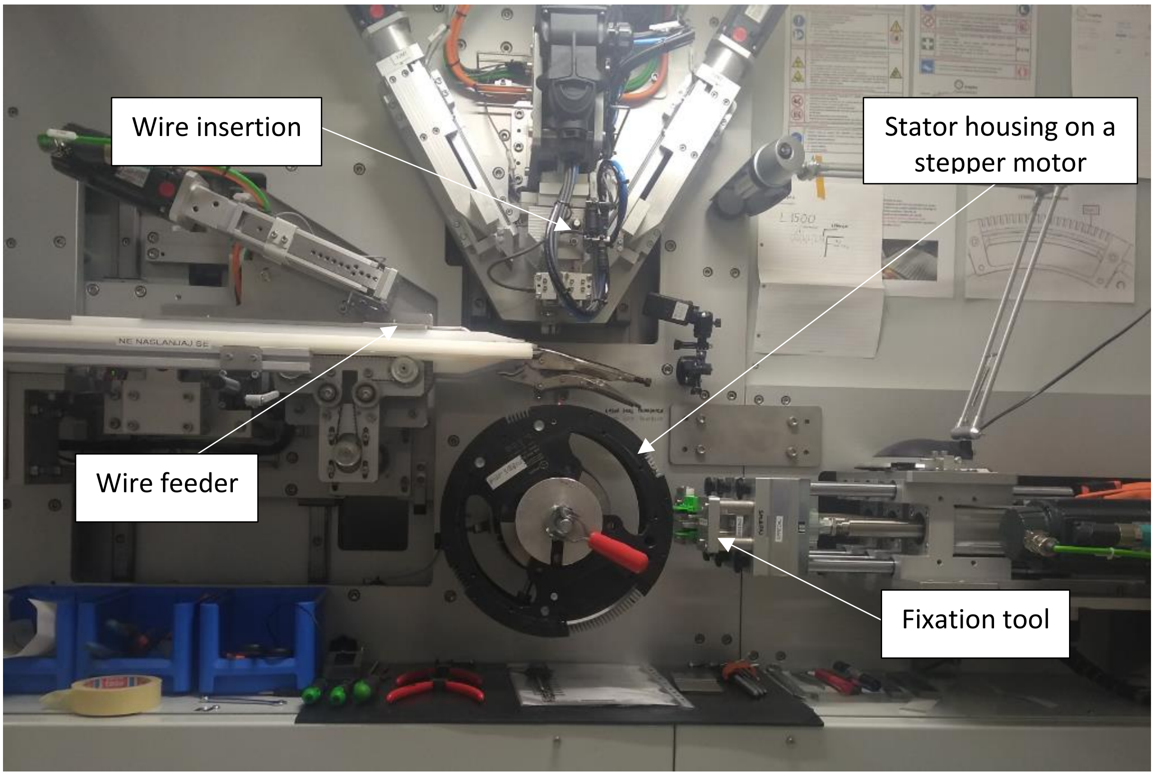


Figure 16 The wire insertion machine.

The wire insertion machine is mostly used for series production of our motors but we decided to use it also for this project since it gives us complete control of the process, we perform on it. All the parameters can be very accurately set and monitored. This way we can achieve repeatability of delicate processes that have to be repeated many times to assemble one motor. The process turned out to be even more complicated with the new wire then what we are used to. The tooling of the machine had to be improved because of this. In early stages we relied on 3D printing as a few iterations were again necessary to get all the parameters right and achieve appropriate fill factor without damaging the wires.

Connecting all the wires with the new geometry was a challenge in itself. This is a task that for prototypes has to be done manually by a skilled operator. Since the fill factors was increased with the new wire, it is much more difficult to work with, compared to the old one. The wire is also stiffer and harder to bend and we also had to be careful about its axial rotation which plays a major part in making it as compact as possible. Elaphe has a specific patented winding type, however the production process was managed by in-house built production machines and developed assembly processes assuring low takt time and high productivity.

We have also improved the durability of the motor by implementing an additional feature connected with wire insulations and protection of the electromagnetically active parts. Significant testing was required to achieve manage all the benefits of this new approach. We also had to figure out the complete assembly process for incorporating this on the motor and we had to develop some specific tools. We had to do some basic validation, with which we finally confirmed the feasibility.

3.3 *Preliminary datasheet for the customized EM parts on M700*

DATASHEET
Date: 1.02.2017
Approved for use by: G. Gotovac | Approved for VD by: L. Ambrozic

elaphe
Propulsion Technologies

CUSTOMER DOCUMENT - Confidential

DATASHEET

Elaphe M700 rD – Sys2Wheel

Water-cooled outer rotor synchronous in-wheel motor with surface mounted permanent magnets

June 2020

3.4 Motor specification

The M700 in-wheel motor basic characteristics are given below. The winding configuration is optimized for a wide operating area with respect to efficiency and speed. At voltages different than nominal, the operating area is proportionally scaled to the voltage increase or decrease with respect to the nominal voltage of the given winding configuration. All values are simulated at 40°C, if not specified differently

Parameter	Value (VD1 EM design spec)	Unit
Supply Voltage (nominal)	355	V DC
Supply voltage (range) for motor	284 – 400	V DC
Boost torque (10 sec) @ 200 rpm	1050**	Nm
Continuous torque (> 30min) @ 780** rpm	500**	Nm
Boost torque phase current	300**	Arms
Continuous torque phase current	120**	Arms
Max. speed (no-load) @ 355 V DC	830** Max speed is simulated at temperature 40°C. At -40°C environmental temperature top speed will decrease by up to 10%. ** At +85°C environmental temperature, the top speed can be increased by 10%.**	rpm
Max. speed (no-load) @ 400 V DC	940** Max speed is simulated at temperature 40°C. At -40°C environmental temperature top speed will decrease by up to 10%. ** At +85°C environmental temperature, the top speed can be increased by 10%.**	rpm
Max. speed (with field weakening) @ 355 V & 300 Nm	1020 rpm** (@300 Nm); 1080 rpm** (no load) @ ID=-75A	rpm
Max. speed (with field weakening) @ 400 V & 300 Nm	1150 rpm** (@300 Nm); 1220 rpm** (no load) @ ID=-75A	rpm
Max. output power (Id = 0) (Net Power; ECE R85) (Torque, speed)	73,7 (640 rpm, 1100 Nm) **	kW

Continuous output power (Id = 0) (30 min power; ECE R85) (Torque, speed)	40,8 (780 rpm, 500 Nm) **	kW
Max. output power with Field Weakening (Id = -75A) (Net Power; ECE R85) (Torque, speed)	73,7 (640 rpm, 1100 Nm) **	kW
Cont. output power with Field Weakening (Id = -75A) (30 min power; ECE R85) (Torque, speed)	39,4 (990 rpm, 380 Nm) **	kW
Max. electric motor efficiency e-machine efficiency	93,8**	%
Max electric actuator efficiency including mechanical losses (such as seals)	93,8** (no contact seals are planned in this version of motor)	%
Max. overall electric actuator wheel efficiency including all mechanical losses such as seals and wheel bearing	93,3**	%
Max. corner efficiency (DC bus to tire efficiency) DC efficiency measured with the recommended inverter, including all mechanical losses in the vehicle corner	91,0**	%
Pole pair number	28**	
Max cogging torque (% of max torque)	<0,1%**	%
Torque ripple (% of max torque)	<5%**	%
Mass torque density (w.r.t. active weight)	>90**	Nm/kg
Volumetric torque density	>529	Nm/l
Coolant type, typical flow	Water/Glycol 50/50; 8 l/min	/
Coolant inlet temperature range for full performance range	-25 to +65	°C
Ambient temperature range for full performance	-25 to +85	°C
IP rating	IP67 and IPX9K	
Active weight	12,1**	kg
Motor mass (excluding brake, bearing and cables)	33,30	Kg

Bearing mass (with bolts) (applicable to standard product only)	4,90			Kg
Bearing load capacity (applicable to standard product only)	Max. lateral force (pure axial) 6,5		Max. radial force (pure radial) 49	kN
Typical vehicle mass limitation w.r.t. cornering	Passenger car 2300 @1,35g lateral acceleration 3000 @1,1g lateral acceleration		Slow cornering vehicles 8000 @ 0,4g lateral acceleration	kg
Available brake types	Disc	Disc with EPB	Without brake	/
Brake sub-assembly mass (including disc, caliper, pads and attachment bolts)	13,5	14,4	3,4	kg
Radial width footprint w.r.t. wheel and hub assembly (applicable to standard product only using a knuckle adapter)	+34,95			mm
Minimal insulation resistance @25°C	10			GΩ
Maximal long-term motor temperature	180**			°C
Maximal short-term (<5s) motor temperature	180**			°C
Operating conditions for full motor performance (intended)	ambient temperature: - 20°C to + 65°C		coolant temperature: -20°C to 65°C	°C
Operating conditions for limited motor performance (intended)	ambient temperature: - 50°C to + 85°C		coolant temperature: -30°C to 65°C	°C
Allowed thermal protection temperatures (intended)	winding temperature: - 40°C to + 180°C			°C

* including all mechanical losses in the vehicle corner

** information based on simulation.

*** According to SAE J2907

****Time from motor thermalized at harshest coolant/environment temperature

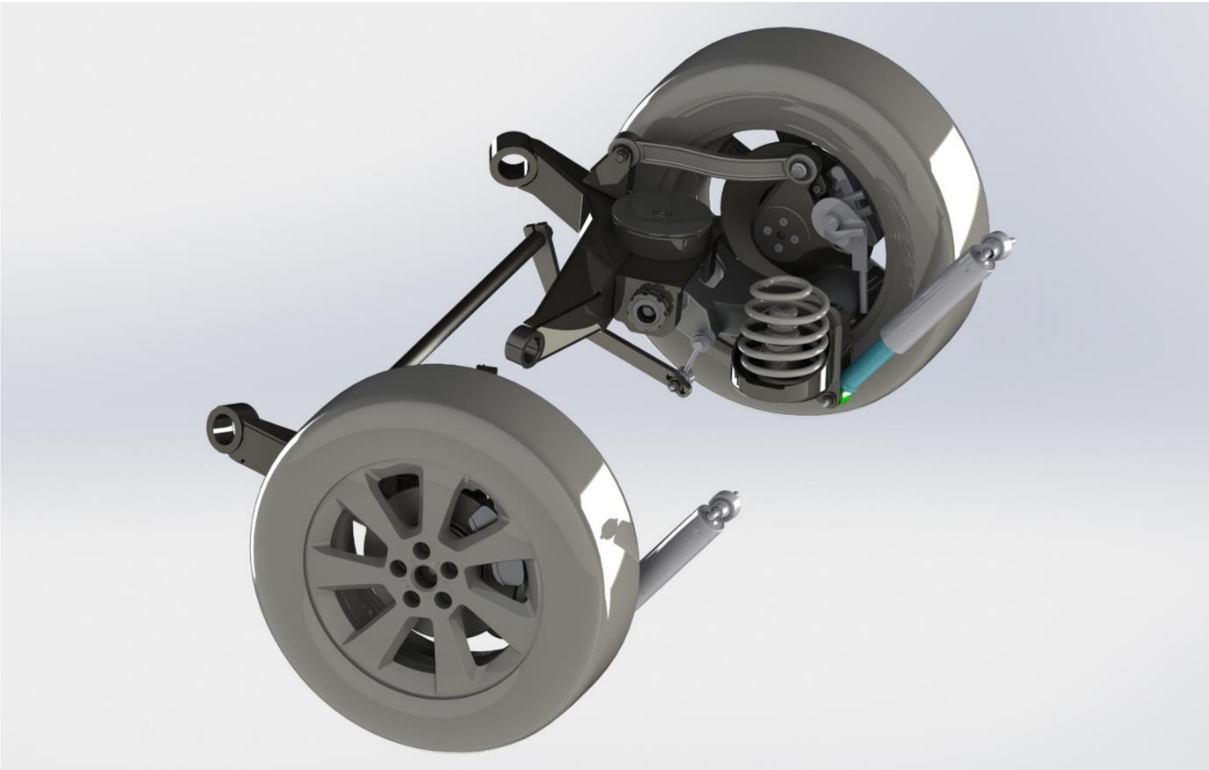
4 Overview of the Suspension System

The suspension system that is contained in the wheel volume. The system allows dynamic behaviour along the wheel travel and chassis roll which gives stability and Comfort travel.

The suspension consists of 3 main parts:

1. Rigid central arm designed to take most of the forces applied on the wheel.
2. Secondary arm designed for only one directional Force.
3. Upright that connects the to arms to the wheel.

In order to mount these arms to the original chassis rigid points we had to create a sub-frame. The subframe serves an additional purpose of silencing NVH and improving travel conditions.



4.1 Main Components and Method of manufacture

4.1.1 Main H arm

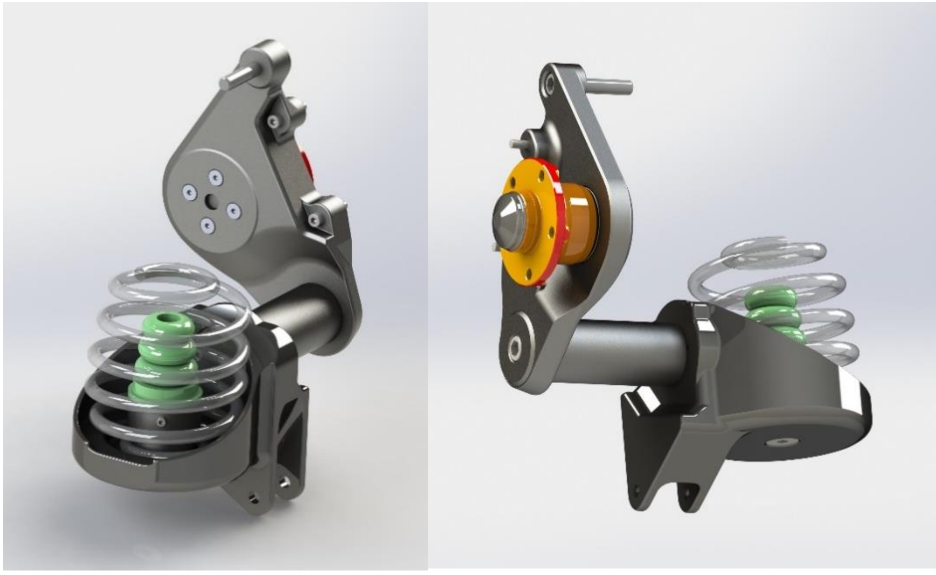
rigid aluminum central arm designed to take most of the forces applied on the wheel. It has to main un parallel axis that crates a dynamic Compensation of Camber and Toe.

4.1.2 Control arm-

secondary arm designed to withstand tension/com[ression forces. The Force in this case is a reaction created by the degree of freedom that appears by the H Arm main Shaft.

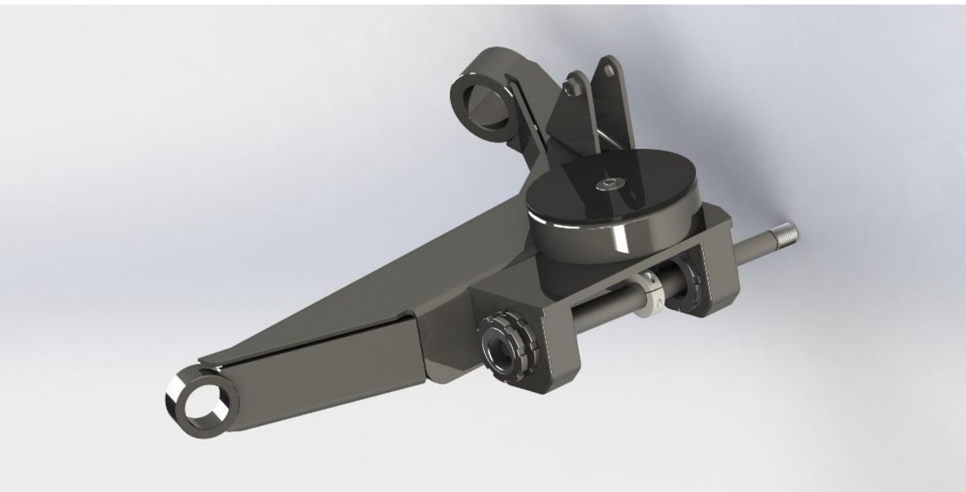
4.1.3 Upright-

The upright connects the arms to the wheel Hub and allows the main arm to pivot while passing the spring and damper reactions from the wheel to the chassis.



4.1.4 Subframe

The sub frame was designed and created in order to allow integration and feeding of forcers of the REE system to the original chassis hard points. On top of that main purpose it allows additional NVH solution and static Toe & Camber adjustments mechanism.

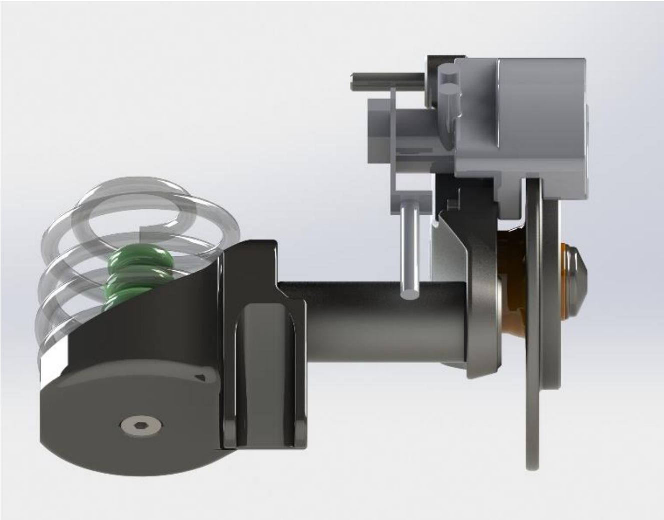


4.1.5 Spring and Damper

Original spring and damper are used and located in their originals points on the chassis side.

4.1.6 Brakes system

The brake system was replaced with a disc brake system. The brakes caliper also includes a mechanical e-brake mechanism.



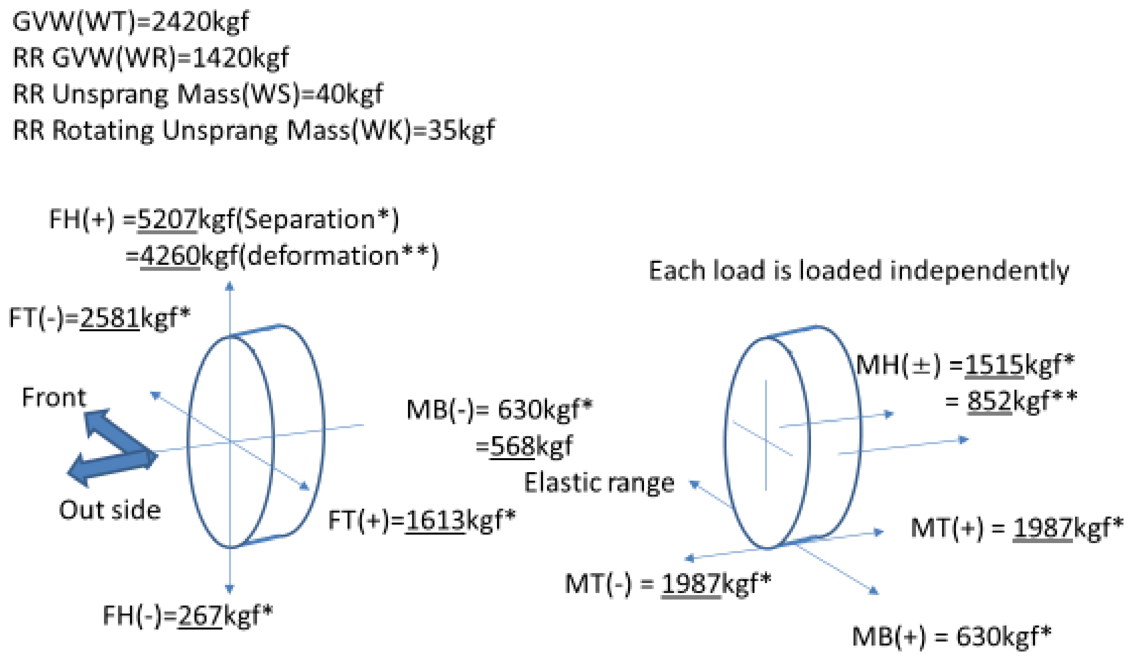
4.1.7 Antiroll bar

Adjustable anti roll bar was attached to the design in order to restore the original design Roll Stiffness.

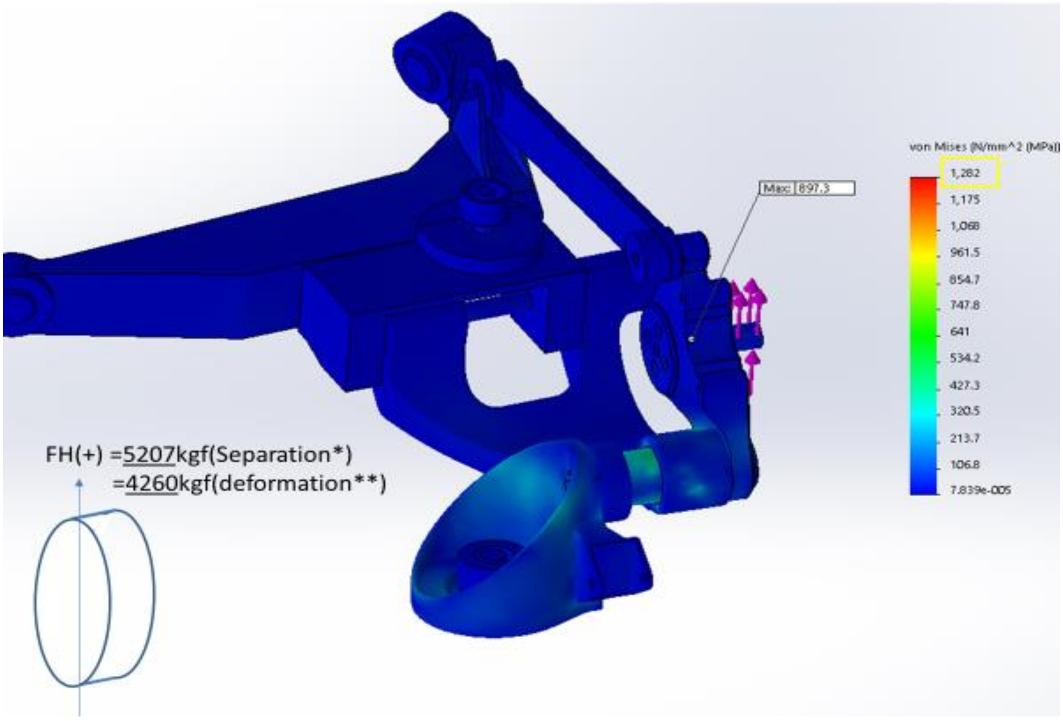
4.2 Analysis

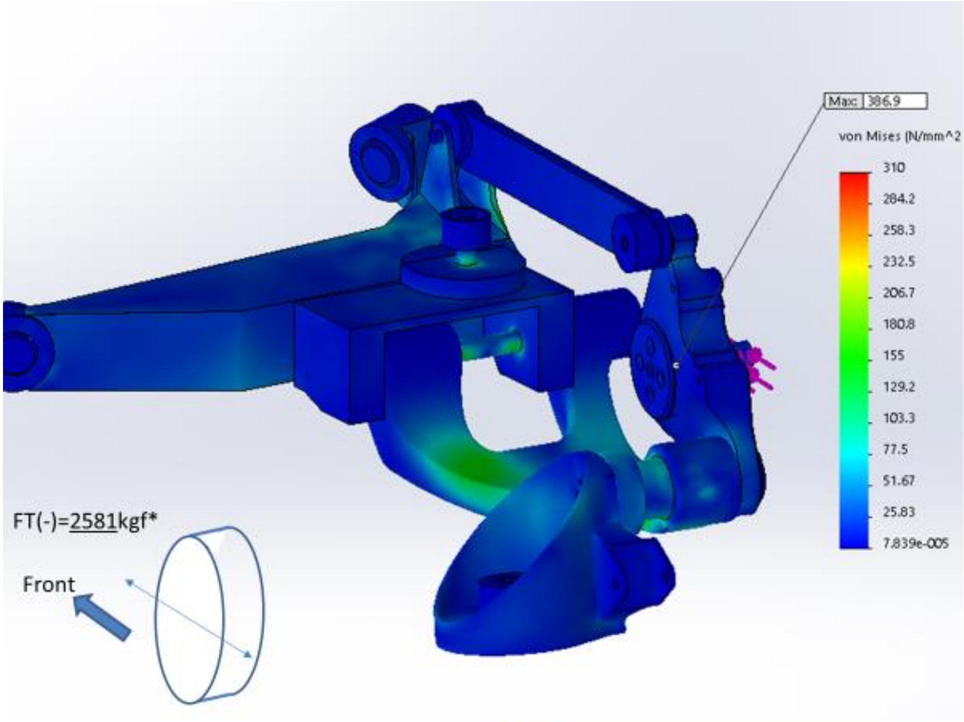
FEA software was used to analyse system design. Relations between the parts of the system were defined and the model was simplified to a level that would test the points we found critical in the design.

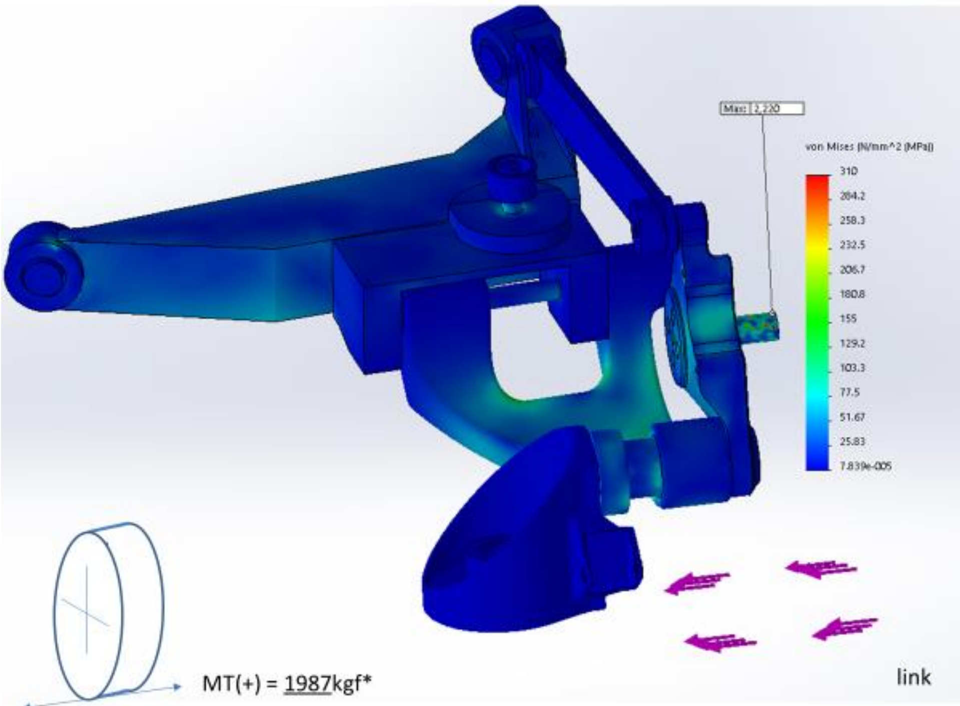
The cases we reviewed are presented in this slide:



Here are some of the critical cases:





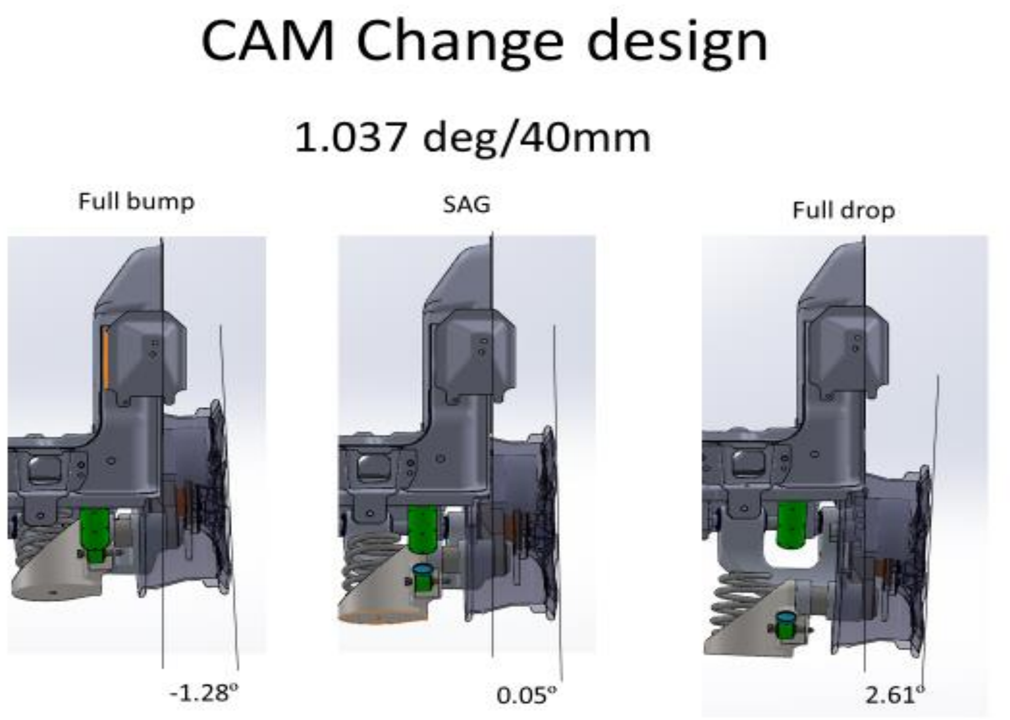


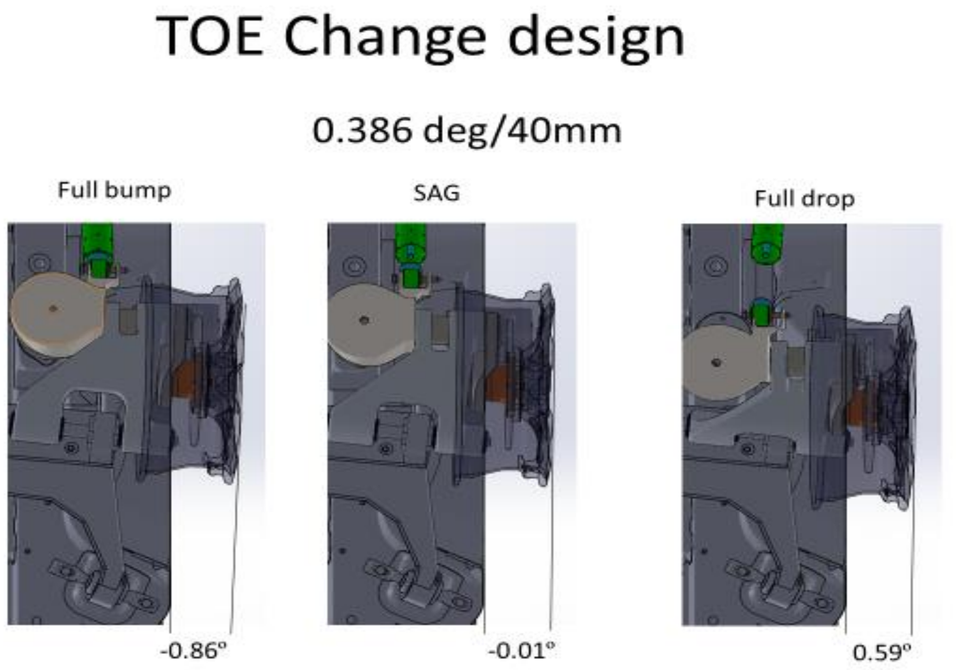
In summary, at this point all the parts we examined met the conditions we set.

Vehicle Dynamics Parameters

The main dynamic parameters that were chosen to focus on are Dynamic Toe and Dynamic Camber.

The results are shown in the following slides:




TOE Change design
0.386 deg/40mm
Full bump
SAG
Full drop
-0.86º
-0.01º
0.59º

5 Abbreviations and Definitions

Table 1: Abbreviation

Abbreviation	Long title
2WD	Two-wheel drive
NEDC	New European Driving Cycle
WLTP	World Harmonized Light Vehicle Test Procedure
EU	European Union
RPM	Revolution Per Minutes
INV	Inverter
TR	Transmission