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Study of Simulation Behaviour of Tire and Effect of Working Conditions on Slipping Behaviour

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Abstract:
This project study implies on creating a workflow which is easily modifiable and deployable. Brake force and Translational velocity are varied to achieve a realistic model of Tire. This model would be helped in future such a way that just changing parameters simulation engineer can achieve a completely different tire model with its respective set of working conditions. The focus of this study is concentrated onto minimize the slip.

Keywords: Abaqus, co-simulation, Dymola, Tire, ABS, Slipping behaviour, DOE, optimization

I. INTRODUCTION

Tires began originally as a durable material circling a fragile wheel such as a steel hoop on a spoke wooden wagon wheel. After the discovery of Vulcanization by Charles Goodyear in 1839, it made rubber a durable and elastic engineering material, good enough for tires for the first time. The concept of radial tires had been introduced in 1914. As it could set its tread on the ground without the squirm and friction of a bias tire, it gave them advantage. In 1962, a Ford engineer named Jacques Bajer and his team put together an experimental piece of test equipment they called a tire-uniformity machine to retrieve dynamic data on what went on as a wheel rolled under pressure. Such machines have since become common place and refined.
Bajer[1] stressed the need to analyze tire, vehicle and road together rather than think of the tire alone. His persistence led to a string of Society of Automotive Engineers; publications explaining numerical analyses of skid and rolling resistance, wet traction, non-uniformity among tires and the behavior of radial tires on Automotive cars. Tire problems are inherently hazardous to vehicle safety. When these problems emerge in the pre-crash phase, the time window for attempting a crash avoidance maneuver is normally very small. Tires that feel fine can hide dangerous defects. Defective tires can cause car accidents that involve: Spinning; Tire blowouts; Skidding; Tires that fall off or away from the vehicle; Hydroplaning (skidding on water); Swerving; Loss of control and Running off the road. In order to create process workflow, which would execute the process through a number of application tools on the system such as Abaqus, Excel, CMD, etc. Simulation Process and Optimization provides a framework for engineering teams to integrate all of the tools they use into re-usable, deployable processes. This reduces time-consuming and error prone tasks to improve productivity and consistency while enabling design exploration studies to find better designs and democratization to expand the user-base for simulation.

II. LITERATURE REVIEW

The main approach used for the study of tire behavior is Finite Element Method (FEM). In this chapter, The Finite Element modeling and analysis of the pneumatic tires are examined in detail and their methodology, assumptions, modeling techniques, investigated parameters and results given in detail. Although the scope of this study is to examine slip behavior of the tires, some studies with different scopes but using similar modeling techniques are presented in literature survey, thus the literature survey of Finite Element tire models is not limited only to slip behavior of tire models. Abaqus technology brief on High-Fidelity ABS Model[2] has been referred. In this technology brief, a co-simulation approach has been used to achieve a realistic system level simulation model of ABS using integration of Abaqus and Dymola. Abaqus has been used to simulate the Tire, Wheel, Brake Caliper mechanism and Road while Dymola has used to simulate Break system algorithm and Hydraulics system. Hub longitudinal velocity and circumferential velocity were compared during co-simulation. Difference between these two quantities is considered as slip. It has found that, the controller is able to prevent wheel lock by applying brake clamping force during co-simulation. Dr. JyotiPrakshRathet.al[3], made a study on optimization of Tire design taken placed by preparing and testing multiple iterations of 175/70R13 tire model. DOE (Design of Experiments) is utilized to identify and optimize critical parameters in tire design. Model analysis was carried out in Abaqus while design parameters were parsed in Hyper study to compute optimization. As Technology Brief for Abaqus, Analysis was took place in four steps. In this study more focus was given on optimizing cornering stiffness of the tire to avoid slip. At first Taguchi Analysis was done to identify critical parameters among all followed by Full Factorial DOE to optimize parameters in order to maximize the cornering stiffness. Study shows that optimization approach with FEA solver gave much appropriate solution over trial and error method. This approach can be well utilized as an automatic tool for predicting tire performance.

III. METHODOLOGY

A. Finite Element Model

The design of tire is generally preferred in steps rather than working with a single model. FEM creation and step assignment are carried out in Abaqus tool. Abaqus is a software application used for both the modeling and analysis of mechanical components and assemblies (preprocessing) and visualizing the finite element analysis result. A subset of Abaqus/CAE including only the post-processing module can be launched independently in the Abaqus/Viewer product. Also Abaqus/Explicit, which is a special-purpose Finite-Element analyzer that employs explicit integration scheme to solve highly nonlinear systems with many complex contacts under transient loads. The design of tire model carried in 5 steps, viz. Axisymmetric, Steady State Revolving, Steady State Transport, Explicit and Restart Explicit. It is preferred to start with axisymmetric modeling. It is been considered as Cost effective way to analyze tires as, Rim mounting, inflation, centrifugal loading etc. can be effectively carried out using a 2D axisymmetric model and 3D geometry generation is simplified through Symmetric Model Generation (SMG) plugins. For axisymmetric model, tire carcass is the main geometric part. Carcass assembly is made of treads, belts, bead, bead apex, carcass, plies and rim. The materials commonly used for reinforcement in tires are nylon and steel. These are modeled as linear elastic or hyperplastic. Material density is required if a subsequent SST or transient rolling analysis is to be performed. Material properties given in Abaqus are given in table 1.

Table .1. Material Properties

Sr. No.	Name	Density	Elastic Properties
1	Nylon	1.5 e-9	E= 10GPa; µ=0.4
2	Rebar	7.5 e-9	E= 75GPa; µ=0.4
3	Capply-Nylon	1.5 e-9	E= 2.5GPa; µ=0.4
4	Rubber	1.1 e-9	-

Rubber shows isotropic hyperelastic properties. Neo Hookestrain potential is provided to specify material properties. The form of the neo-Hooke strain energy potential is

$$U = C_{10}(\bar{I}_1 - 3) + \frac{1}{D_1}(J^{e\ell} - 1)^2,$$

where, U is the strain energy per unit of reference volume; C10and D1are temperature-dependent material parameters; I1 is the first strain invariant depends on J, the total volume ratio; λ, elastic volume ratio and are the principal stretches. Rim is mounted on tire with Automatic shrink fit in the position. A general contact between rim and carcass is defined with smoothing factor of 0.2. All degrees of freedom except the axial one is kept fixed. Axial motion of the rim may be desired if the rim is instanced in the assembly at a location other than the mounted position. Inflation pressure of 0.25 MPa is applied on carcass.

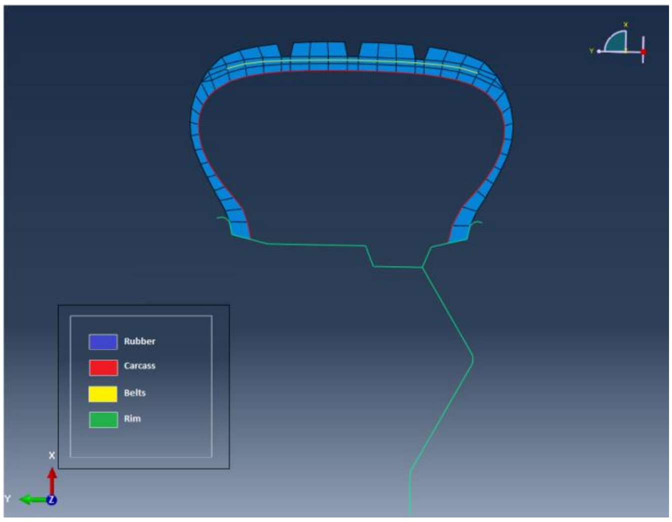

Figure.1.Axisymmetric section of tire model

Abaqus provides the capability to generate a three dimensional model from asymmetric model and then transfer the solution obtained from the symmetric analysis to the new three-dimensional model. This Model generation and results transfer is possible from: Symmetric Model Generation (SMG): Revolve or Reflect type and Symmetric Results Transfer (SRT). A typical load sequence may start with rim mounting, followed by inflation; a “footprint analysis,” where contact between the tire and the road is established; and, perhaps, a rolling analysis. The deformation in the subsequent footprint analysis, however, is no longer Axi-symmetric, so a three-dimensional model is required to continue with the analysis. The results transfer capability allows the user to transfer the solution obtained at any stage of the axisymmetric analysis to the new three dimensional models. These results serve as the initial or base state in the new three dimensional analyses.Inflated 3D tire comes in contact with road. The coefficient of friction between road and tire is taken as 0.8, and that between braking pad and disc is taken as 0.4.

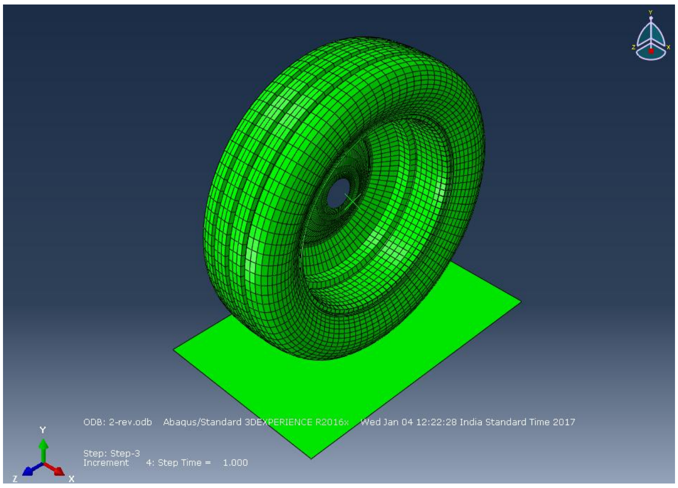

Figure.2.Revolved 3D Tire

It is followed by steady state transport analysis which requires the definition of streamlines. The streamlines are the trajectories that the material follows during transport through the mesh. To meet this requirement; the mesh must be generated by using SMG. For models generated by revolving a two-dimensional cross-section about a symmetry axis, the streamlines follow the mesh lines. Since the slip on the contact surface is expressed in terms of the deformation of a streamline, special interface calculations are required when modeling rolling contact. However, since the frictional model used for steady-state rolling is different from the frictional models used with other analysis procedures in Abaqus, discontinuities may arise in the solutions between a steady-state transport analysis and any other analysis procedure, such as a static footprint analysis. Transport velocity is a parameter which is varied for optimization to get optimized results. Explicit analysis carries transient dynamic analysis of tire. Braking analysis is carried out on the tire model obtained from Analysis 4 (rolling simulation) i.e. in Explicit Step. 4 KN Load (corresponding 400kg: quarter of vehicle weight) is applied at center of wheel. Friction between tire and road is taken as 0.8, and that between braking pad and disc is taken as 0.4. Also, in this step external input file is included which contains brake paddle geometry. This is considered as analytical rigid body. The force is applied as a connector load (defined using an amplitude) which pushes the braking pad against disc. In the previous workflow, the amplitude of this force was input by Dymola. In current workflow, we are using the amplitude in the adjoining figure, in which the force is ramped up to 1 N in 0.05 sec and then held constant for rest of the simulation. This amplitude is scaled using a scale factor in Y (SCALEY) which is defined as a parameter brake_force. This parameter is varied DOE, along with translational velocity. Results of this step are generally not used to determine end use properties of tire as the step would be restarted in next step. Transient Dynamic analysis for tire model which takes place on 4th step is restarted in final step. In this step the brake force is applied on brake pad and disc. In without ABS model this value is not depending on slip or slip rate. Thus, tire shows behavior to slip. However in ABS Dymola co-simulation approach the tire tends to fewer skids as brake force is variable in nature rather than constant in value. This behavior explains about Anti-Lock Braking (ABS) system in modern vehicle. During Explicit analysis, non-iterative co-simulation scheme is used integrating Abaqus and Dymola for braking. Abaqus computed state of stress and deformation in rolling tire. Wheel angular velocity and acceleration are communicated to Dymola through Abaqus sensors. Required braking force was computed by Dymola which further communicated back to Abaqus. Out of various parameters which effects on slipping behavior of tire, following were selected.

1 **Input Parameters:**
   a. Brake Force: 0 to 45 KN
   b. Translational Velocity: 0 to 80 kmph
   c. Angular velocity=Trans_vel/rollradius
2 **Constant Parameters:**
   a. Inflation pressure = 0.25 MPa
   b. Coefficient of friction between tire and road = 0.8
   c. Coefficient of friction between braking pad and disc = 0.4
   d. Hyper-elastic Material Properties for Rubber i.e. C10 & D1: C10 = 123.046& D1 = 0.0116
3 **Response variables: Stopping Distance**

B. Dymola ABS Model

ABS stands for Anti-lock Braking System, is an automobile safety system that allows the wheels on a motor vehicle to maintain tractive contact with the road surface according to driver inputs while braking, preventing the wheels from locking up and avoiding uncontrolled skidding. Typically ABS includes a central electronic control unit (ECU), four wheel speed sensors, and at least two hydraulic valves within the brake hydraulics. The ECU constantly monitors the rotational speed of each wheel; if it detects a wheel rotating significantly slower than the others, a condition indicative of impending wheel lock, it actuates the valves to reduce hydraulic pressure to the brake at the affected wheel, thus reducing the braking force on that wheel; the wheel then turns faster. Conversely, if the ECU detects a wheel turning significantly faster than the others, brake hydraulic pressure to the wheel is increased so the braking force is reapplied, slowing down the wheel. This process is repeated continuously and can be detected by the driver via brake pedal pulsation. Some anti-lock systems can apply or release braking pressure 15 times per second. Because of this, the wheels of cars equipped with ABS are practically impossible to lock even during panic braking in extreme conditions. Dymola modeling behavior is used to build a logical model for ABS system. Dymola – dynamic Modeling laboratory is suitable to simulate the dynamic behavior and complex interactions between systems of many engineering fields, such as mechanical, electrical, thermodynamic, hydraulic, pneumatic, thermal and control systems. Dymola environment uses an open source, object oriented, and equation based language called Modelica. The figure illustrates ABS Dymola model. The model is mainly consists of different blocks.

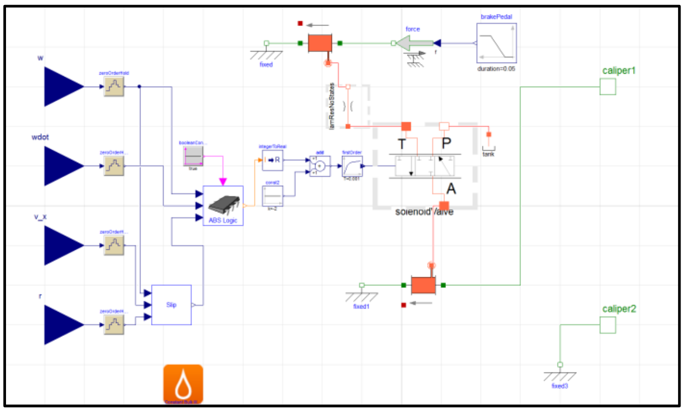

Figure.3. ABS Dymola model

In the first block, slip is calculated. Slip is the relative motion between a tire and the road surface it is moving on. This slip can be generated either by the tire's rotational speed being greater or less than the free-rolling speed. Thus, slip is a function of angular velocity, linear translational velocity and rolling radius. Mathematically, slip is defined as

$$\lambda = \frac{V_x - r\omega}{V_x}$$

Where, λ = longitudinal slip,
V_x= Hub longitudinal velocity,
r = Rolling radius,
ω = Angular velocity.

Next block, ABS Logic is a controller which is provided with input of angular velocity, angular acceleration and slip calculate from slip block. The controller is a control unit for ABS system. It gets input from various devices and accordingly provides signal to proceeding units. The valve actuation signal provided from controller directly given to solenoid valve. This signal is generally in Boolean format i.e. ON or OFF response. ON specifies solenoid valve to open the circuit and OFF provides closing the circuit. In this way application and releasing of breaks takes place, which is nothing but working principle of ABS. Force input to solenoid valve is given by brake paddle. Brake paddle force is complete function of end user. The main actuating part of ABS model is a Solenoid valve. A 3 way 2 port valve is used. A solenoid valve is an electromechanically operated valve. The valve is controlled by an electric current through a solenoid: in the case of a two-port valve the flow is switched on or off; in the case of a three-port valve, the outflow is switched between the two outlet ports. Brake paddle is further attached to damping cylinder which absorbs pressure fluctuations. Also solenoid valve is attached to caliper and master cylinder which absorbs pressure fluctuations.

C. Process composer workflow

Simulation Process Composer provides the simulation the set of adapters that can be simply Configured and connected to form a workflow. Process adapters (such as Loop, DOE (Design of Experiments) and Optimization) will form matrix for design space and sub-flows will run multiple times according to algorithms embedded and are used to drive the workflow. Function adapters (such as Calculator, Abaqus, Excel, Script, etc.) perform a specific function and can involve an application that is external to Process Composer. Using the simulation process adapters and varying input parameters as per requirements a workflow of surrogate model is to make in process composer. And another workflow of co-simulation between Abaqus tire model and ABS Dymola model is also to be made to find the optimize solution. Those two workflows are shown in figure 4 and 5.

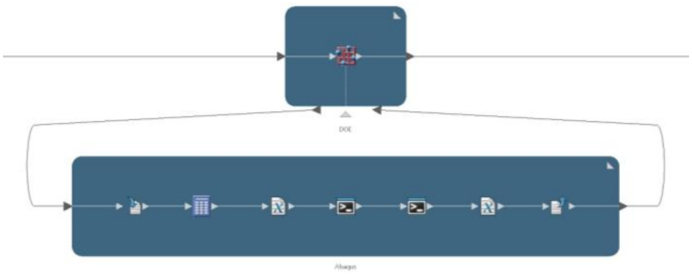

Figure.4. Workflow- Tire workflow without ABS

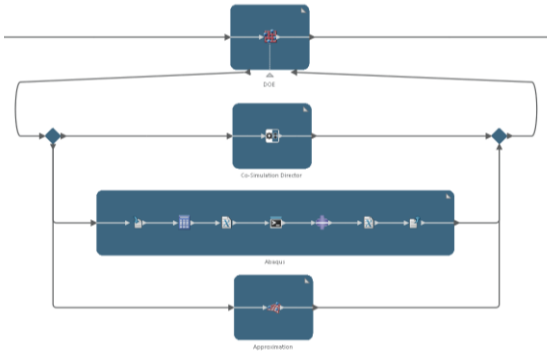

Figure. 5.Workflow- Tire workflow with ABS

Both the workflows are created in SIMULIA Process Composer App. The first workflow, as in fig. 4, is built for without ABS model i.e. it would execute without integration of Dymola model. DOE Latin Hypercube method is firstly used to see the effects of changing the parameters on model. First download adapter will download required Abaqus .inp file, python scripts which would require executing in working directory. Next calculator adapter is put for unit conversion of velocity. Input velocity is given in kmph while abaqus require velocity in mm/sec. Thus conversion takes place by multiplying 5/18. Text adapter writes input varying parameters in parameter input file which will include in step files. OS command will execute abaqus job file and python scripts one after another using commands. Second text parser will read the stopping distance at the end of step and will use to draw a graph in Excel. Second workflow, as in fig. 5, is built for co-simulation between Abaqus and Dymola. Abaqus activity is copied as it is from first workflow. Further addition of parallel activities of co-simulation director and approximation. Co-simulation director execute the co-simulation as per xml file provided. From 5th step i.e. explicit step exchange between Dymola and Abaqus is takes place. Break paddle force, Translational velocity, angular velocity, angular acceleration and rolling radius are output from Abaqus which are input for Dymola. Dymola will produce output for Brake force which will be given as input for Abaqus and braking action will takes place. Following images show screenshots from actual 3Dx Process composer. Fig. 6 shows input varying factors with their ranges while fig 7 shows output response. The workflow used for DOE technique is the same for Optimization adapter, except it work under Optimization Process adapter.

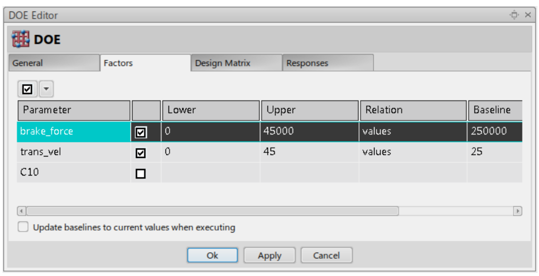

Figure.6. Input parameters

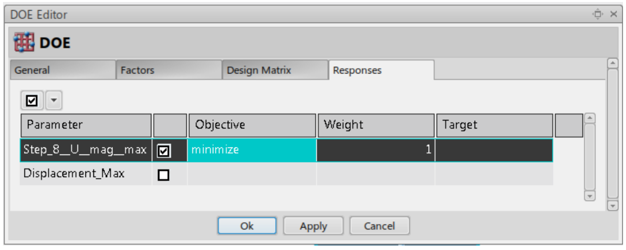

Figure.7. Response parameter

IV. RESULTS AND DISCUSSION

Following are the results that can be concluded by execution of workflow built. On successful execution of workflow process on Server client, it generates a result table which has given below. A simulation engineer can study and conclude the observation. Result graphs are also can be plot by using python script. Process composer application automates the whole process in order to execute process with very little interference of user. Number of application tools like Abaqus, Dymola, MS Excel, MS CMD, python etc. can be used without actually switching into application interface. The following results are drawn by observing and studying the table generated by process composer adapters.

1. In general, stopping distance reduces with increase in braking force, while the velocity shows direct proportion with the stopping distance. As velocity increases, at constant braking force, stopping distance increases too.
2. It was observed that, there is an optimum value of force magnitude, (100 kN in this case), above which there is not much reduction in stopping distance.
3. Slip doesn't vary a lot by varying C10 constant or friction between road and tire.
4. Slip also depends on braking force. There is a critical value of braking force above which slip starts
5. Braking force magnitude has an optimum value for stopping distance. Increasing braking force above this optimum value doesn't decrease the stopping distance by large amount

Table.2. DOE Results (Force vs. Stopping Distance)

Iter	C10	D1	Force	Stopping Distance
1	123.046	0.0116	20	18176.6
2	123.046	0.0116	40	10618.4
3	123.046	0.0116	60	8041.61
4	123.046	0.0116	80	6835.84
5	123.046	0.0116	100	6523.42
6	123.046	0.0116	120	6450.01
7	123.046	0.0116	140	6489.56
8	123.046	0.0116	160	6493.48
9	123.046	0.0116	180	6489.49
10	123.046	0.0116	200	6480.68

Table .3. DOE Results (Velocity vs. Stopping Distance)

Iter	C10	D1	Velocity(kmph)	Stopping Distance
1	123.046	0.0116	0	0
2	123.046	0.0116	10	46.72
3	123.046	0.0116	20	156.8
4	123.046	0.0116	30	746.2
5	123.046	0.0116	40	1782.1
6	123.046	0.0116	50	3164.4
7	123.046	0.0116	60	4279.9
8	123.046	0.0116	70	6024.13
9	123.046	0.0116	80	6523.42

Table.4. DOE Results for co-simulation execution (Brake Force vs. Stopping Distance)

Iter	C10	D1	Force (kN)	Stopping Distance
1	123.046	0.0116	20	13503.8
2	123.046	0.0116	40	8961.4
3	123.046	0.0116	60	6741.1
4	123.046	0.0116	80	5935.47
5	123.046	0.0116	100	5833.14
6	123.046	0.0116	120	6085.8
7	123.046	0.0116	140	6199.17
8	123.046	0.0116	160	6593.81
9	123.046	0.0116	180	6859.1
10	123.046	0.0116	200	7098.8

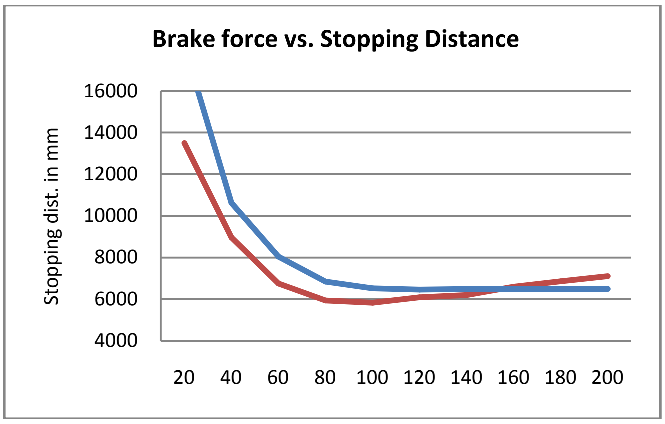

Figure.8. Comparison between ABS and Non-ABS braking behavior

V. SUMMERY AND CONCLUSION

The study has focused on creating a work flow which is easily modified for different tire model, different working conditions, loading conditions, and co-simulation. It has estimated that use of process composer workflow reduces time-consuming and error-prone tasks to improve productivity and consistency while enabling design exploration studies to find better designs and democratization to expand the user-base for simulation. Simulation Process and Optimization provides a framework for engineering teams to integrate all of the tools they use into re-usable, deployable processes. The process without flow will require human interaction to switch between tools being used. A general timeline shows it requires around 5 hrs and 30 min to complete each iterations without co-simulation, while with co-simulation time reaches around 9 hours to complete single iteration. By using Process Work-flow, the whole process is being automated such that by single click complete workflow is executed. The only limitation about the workflow is machine should not logged-off, the workflow does not consider log-off criteria. Future studies can include a use of different sets of analysis for same or different models. By using workflow created in process composer, one can automate the simulation process with very less or no human interaction. Following are some examples of the studies can be done.

1. Considering non-linear explicit working condition to study slipping behavior in a tire.
2. Comparison between results taken from non-ABS System and ABS system
3. Optimization model instead of DOE to show a relationship between brake force and velocity on stopping distance of tire under prescribed conditions.
4. Application of design parameters of a tire, such that, a single workflow will consider no. of tire designs at the same time in a single set of executions..

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