Hydroplaning Simulation using MSC.Dytran

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ABSTRACT

Hydroplaning characteristics is one of the key functions for safety driving on wet road. Since hydroplaning is a complex phenomenon involving coupling between tire deformation and surrounding fluids, implementation of three-dimensional numerical methods have been slow and needs to wait until late nineties.

The numerical analysis procedure to predict the onset of hydroplaning of a tire is proposed here, considering the vehicle velocity dependency. MSC.Dytran is used to solve coupled problems between tire deformations and surrounding fluid. A reference flame fixed on a moving car is used to simulate transient phenomena effectively. Complex geometry of tread pattern and rotational effect of a tire, which are important functions of hydroplaning simulation, and also dependency on vehicle velocity are included in the proposed procedure.

To verify the feasibility of the procedure, predicted hydroplaning velocities for four different simplified tread patterns are compared with experiments measured at proving ground. A comparison supports the effectiveness of the numerical simulation of hydroplaning. Lastly, numerical examples for the newly developed tires are also presented.

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INTRODUCTION

Hydroplaning is the phenomena, in which frictional force diminishes between tire and road surface, when a vehicle drives on a wet road covered by water film. The phenomenon is thought to be caused by the pressure increase of the water film above the contact pressure of tire and road. Since hydroplaning is a complex phenomenon involving coupling between tire deformation and surrounding fluids, implementation of three-dimensional numerical methods have been slow and needs to wait until late nineties.

Grogger et al. [1-2] did the pioneering work and numerically solved hydroplaning phenomenon, using combination of general-purpose packages of fluid dynamics and in-house code of structural analysis. They defined fluid meshes around contact area of a deformed tire and their velocity and pressure fields were obtained. Their models were limited to smooth or longitudinal only grooved tires, which do not rotate. Afterward, Seta et al. [3] extended the work to rotating tires with complex tread patterns and solved hydroplaning, using MSC.Dytran, as the coupled problem between tire deformation and pressure field of surroundings fluid. In either case, however, prediction of the hydroplaning velocity, which is an important index of hydroplaning characteristics of a tire, was not achieved.

In the following, general discussion of hydroplaning simulation will be made in which velocity dependency of rotating tires is accounted. And then, using MSC.Dytran, which handles coupled problem between structure and fluid, a procedure is proposed to predict the onset of hydroplaning of a tire. The method is used to predicts the hydroplaning performance index, i.e. “hydroplaning velocity”.

HYDROPLANING PHENOMENON OF A TIRE

The condition of the interface between tire and road during hydroplaning is explained, using well known “three zone concept [4]” and shown in Figure 1. Three regions about the interaction of tire and road is defined as:

Region A (Bulk Zone)	: Complete Hydroplaning Region
Region B (Thin Film Zone)	: Partially Hydroplaning Region
Region C (Dry Zone)	: Complete Adhesion Region

In region A, dynamical pressure, due to collision of water and tire, lifts the tire. In region B, thin water layer exists and due to the influence of viscous lubrication of water, tire is partially lifted. In region C, no water film exists and tires adhere to the road completely.

When a vehicle drives at low speed, region C dominates the contact patch, in which no water film exists between tire and road. As the vehicle velocity increases, dynamical pressure of water tends to lift the tire and region A becomes dominant. When a tire is completely lifted, region C diminishes. The present hydroplaning simulation targets the “region A” and by analyzing the dynamical pressure by collision of water film and a tire-front edge end lifts a tire, hydroplaning velocity is to be predicted, which is an important hydroplaning performance index of a tire.

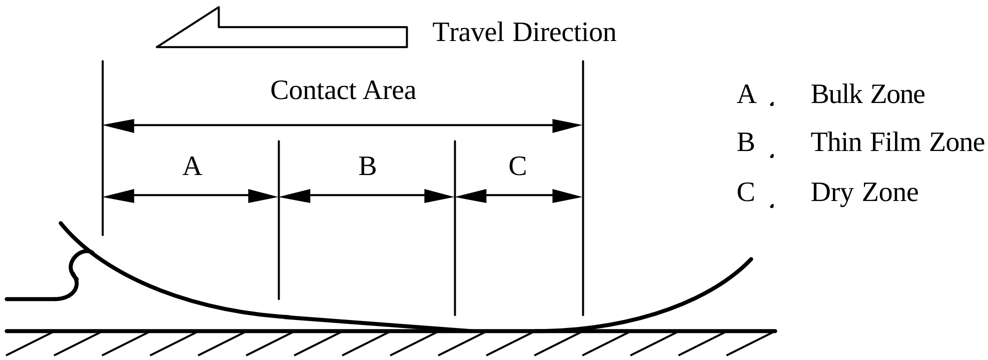

Figure 1. *Three Zone Concept*

HYDROPLANING SIMULATION OF A TIRE

MSC.Dytran is an explicit-type code to solve coupled problems between tire deformation and surrounding fluid. Tire deformation is solved using FEM and fluid behavior is solved using FVM, respectively. For the analysis, tire is modeled by Lagrangian formulation and fluid is modeled by Eulerian formulation, as depicted in Figure 2. The coupled problems between tire deformations and surrounding fluid is treated using "General Coupling Algorithm [5]".

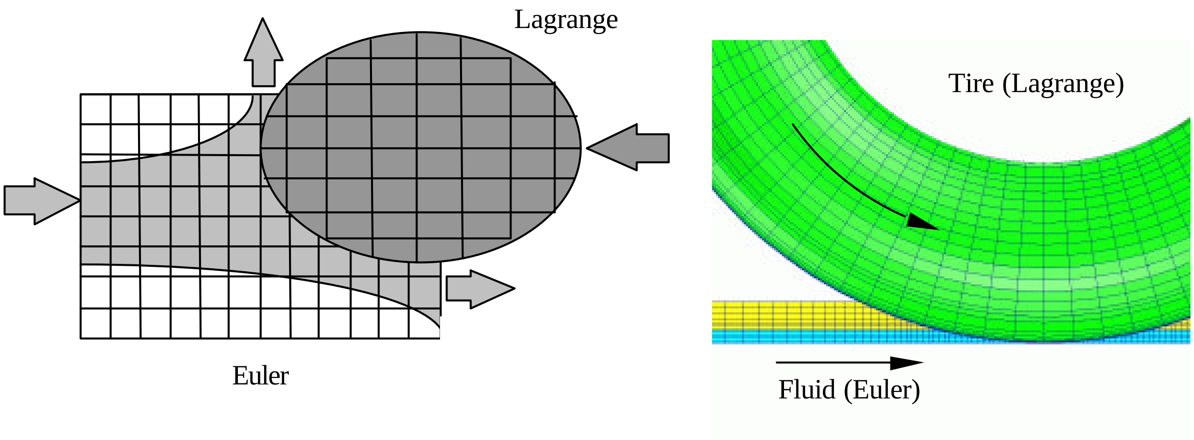

Figure 2. *General coupling function and hydroplaning simulation model*

Modeling of a Tire

Since MSC.Dytran adopts "Central Difference" scheme in time integration, stability limit exists to determine the stable time increment (Courant criterion). Transition time of a dilatational wave across an element is known to follow:

$$? t ? \;\; L / S, \qquad S = v(?/?) \qquad (1)$$

Where, ? t : time increment,

L : smallest specific element length,

S : dilatational wave speed,

? : dilatational modulus and

? : density of materials

The smallest element length in the model determines the stable time increment. In the case of using fine mesh, number of iteration increases to attain the target physical time. In the case of using higher elastic modulus material, time increment is decreases, as a result, number of iteration increases too. Sufficient care is needed for the modeling of a tire.

Tires are composite material structures comprises of some parts, which are carcasses, belts, cap tread, side tread and bead core, as illustrated in Figure 3. Among them, carcass and belt have high elastic modulus and also thin composite materials. If they are modeled using continuum elements, its thickness determines the magnitude of "time increment". Therefor, thin composite materials, such as carcass and belt, are modeled using multi layered shell elements. And also, bead core has very high elastic modulus and causes the same problem of increasing number of computational iterations, if modeled using continuum elements. Therefore, bead core is modeled as rigid elements. All other parts of tire constructions are modeled with 8-nodes continuum elements.

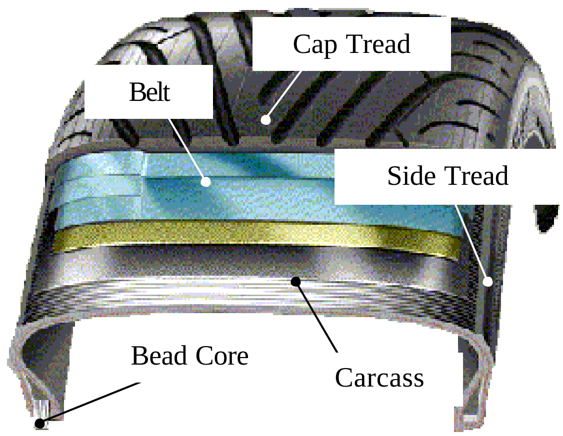

Figure 3. *Construction of a Tire*

For the hydroplaning performance, tread patterns of a tire plays important part. As for the modeling of a tire with tread pattern using finite elements, tire body portion and geometrically complex tread portion are modeled separately first, and then combined to each other, by sticking them with rigid connection, as illustrated in Figure4. Usage of rigid connection in this fashion eliminates the necessity of coinciding nodes at the interface surface between tire and tread pattern, enabling the FEM modeling of tread patterns with complex and arbitrary shapes.

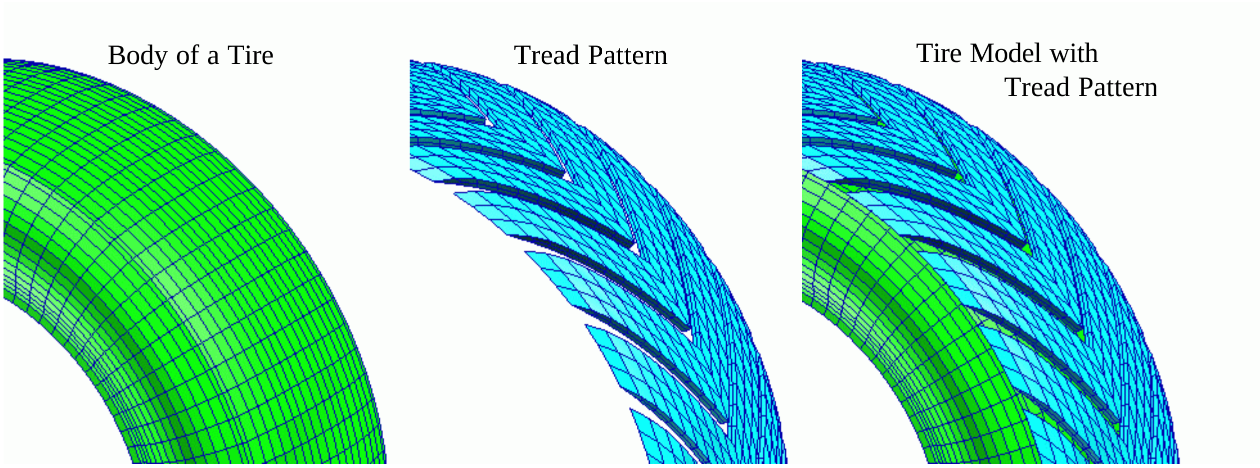

Figure 4. *Finite element model of a tire with tread pattern*

Modeling of a Water Film

In hydroplaning simulation, modeling of water layer is as important as modeling of tire structure. Water layer is modeled using 8-nodes continuum elements. Having bottom surface of water layer coincide to road surface which was modeled as rigid body, water layer is defined on the upper side of the road surface whose thickness is 10mm. On top of the water layer, a vacant space called "void" is defined to enable water scattering. By defining the Eulerian elements initially, where water is expected to move in later on, free surface of water can be simulated and enables the analysis of water scattering drained by tread patterns. Element size of water layer needs to be less than or equal to the tire groove width. However, if finer meshes are adapted to the entire region of water layer, the computation time becomes impractical.

To obtain sufficient numerical accuracy and also to reduce CPU time, water layer around contact area, where deformed tire and fluid interfere, is equally divided into small size meshes. In the other region away from contact region, the sizes of mesh are increased according to the geometric ratio, as shown in Figure 5. In the present study, water is assumed to be compressible and also a laminar flow.

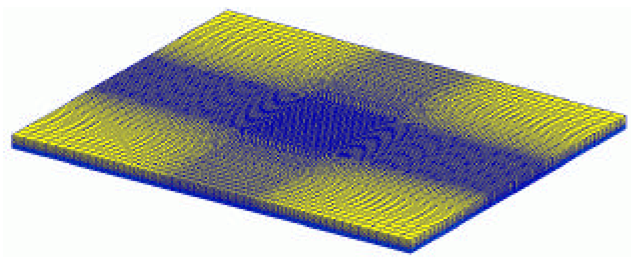

Figure 5. *Finite volume model of a water*

Coupled Structure - Fluid Problem

MSC.Dytran has two types of function of coupling, to solve coupled problems of structural deformation and surrounding fluid flows. One is ALE (Arbitrary Lagrangian - Euler) coupling function and the other is General Coupling Function. ALE coupling moves the nodes in eulerian formulation, in accordance with the movements of nodes in lagrangian formulation. When dealing with extremely complex shapes, such as tread patterns, problems arise: 1) coincidence of tread nodes and fluid nodes become difficult, 2) fluid elements becomes so distorted when tires moves in the water layer with rolling motion that elements collapse eventually. And therefore, usage of ALE Coupling is not appropriate for hydroplaning simulation with complex tread pattern geometry.

On the other hand, General Coupling Function enables tire deformations to couple with surrounding fluid, by overlapping on the fluid elements, as shown in Figure 6. In this case, by definition of shell elements on structure as a coupling surface, the interface surface between Lagrangian and Eulerian elements automatically updated and boundary conditions are automatically computed during simulation. Only by taking advantage of General Coupling Function, one can model hydroplaning phenomena in which surrounding fluid is drained by the tire, which has complex tread pattern geometry.

Numerical Procedure Considering Vehicle Velocity Dependency

Main objective of the present study is to predict the onset of hydroplaning phenomenon based on the analysis of velocity dependence of contact force between tire and road. Theoretically, hydroplaning phenomenon should be modeled as a rotating tire moving on the road covered with water layer. However, such an approach necessarily needs finer meshes over the entire region of water layer in which the tire is expected to roll on, leading to an impractical size of number of elements.

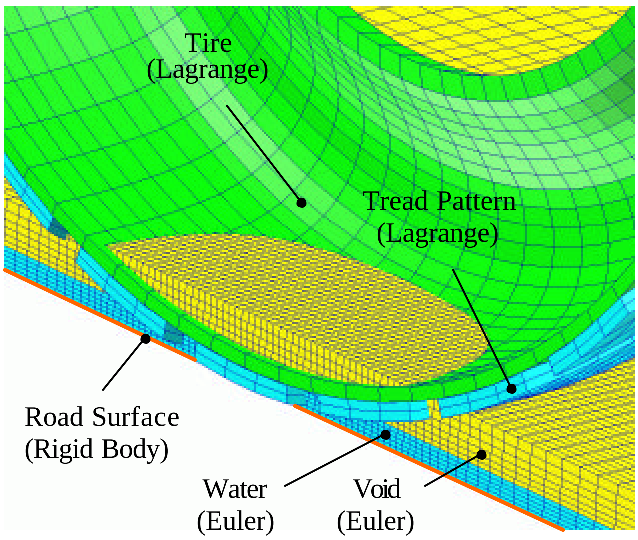

Figure 6. *Models of coupled problem of a tire and water film*

To cope with the problem, moving reference frame fixed on the traveling vehicle is adopted. Instead of tire moves on the fixed road, the transverse velocity is applied to the road and the tire rotates at the fixed position. Simultaneously, inertial force is applied to the fluid so that the same velocity as the road surface is generated. Thus, one can simulate the process, in which the contac t force between tire and road reduces as the flow velocity increases and dynamical pressure of water lifts tire incrementally. By the relationships between fluid velocity and contact force thus obtained, “Hydroplaning velocity” can be determined.

Here, hydroplaning velocity in the simulation is defined by the transverse velocity, at which the contact force between tire and road reduces to 10% of the tire load. And also, velocity of the road and the fluid are increased from 0 km/h initially, to 120 km/h at the end, with constant acceleration. Road is modeled as smooth rigid surface. Both static and dynamic friction coefficients are assumed to be 1.0.

NUMERICAL VERIFICATIONS

To verify the feasibility of modeling and numerical methods thus far stated, the predicted hydroplaning velocity for four different simplified tread patterns are compared with experiments measured in proving ground. Four simplified tread patterns are 1) smooth tire, 2,3) two longitudinal groove tires (narrow groove = groove width 9mm, and wide groove = groove width 18mm), and 4) V-shape grooved tire. Since V-shape grooved tire has different hydroplaning velocities according to the normal and reverse rotational directions; closer look will be taken. Specifications of test tires are, tire size: 195/65R15, vertical load: 4kN, and inflation pressure: 200kPa.

Table 1. *Hydroplaning Test Conditions*

Vehicle	Passenger Car (FR)
Tire Size	195/65R15
Rim	15×6JJ
Inflation Pressure	200 kPa
Water Depth	10 mm

Figure 7. *Hydroplaning Test in Proving Ground*

Hydroplaning Test in Proving Ground

Prior to hydroplaning simulations, four different test tires with simplified tread patterns are produced and the experiments evaluating the hydroplaning characteristics in straight-ahead is carried out. In the experiment, the relationships between vehicle velocity and slip ratio of each tire are measured when a vehicle runs on hydro pool whose water depth is 10mm. Figure 7 shows the view of hydroplaning test at proving ground and test conditions are listed in Table 1. Also, visual images of water flow around the contact area when tires runs on water film are recorded using high-speed video camera.

The relationship between vehicle velocity and slip ratio of a tire is shown in Figure 8. The slip ratio of the tire increases gradually as the vehicle velocity, driving in water pool, increases.

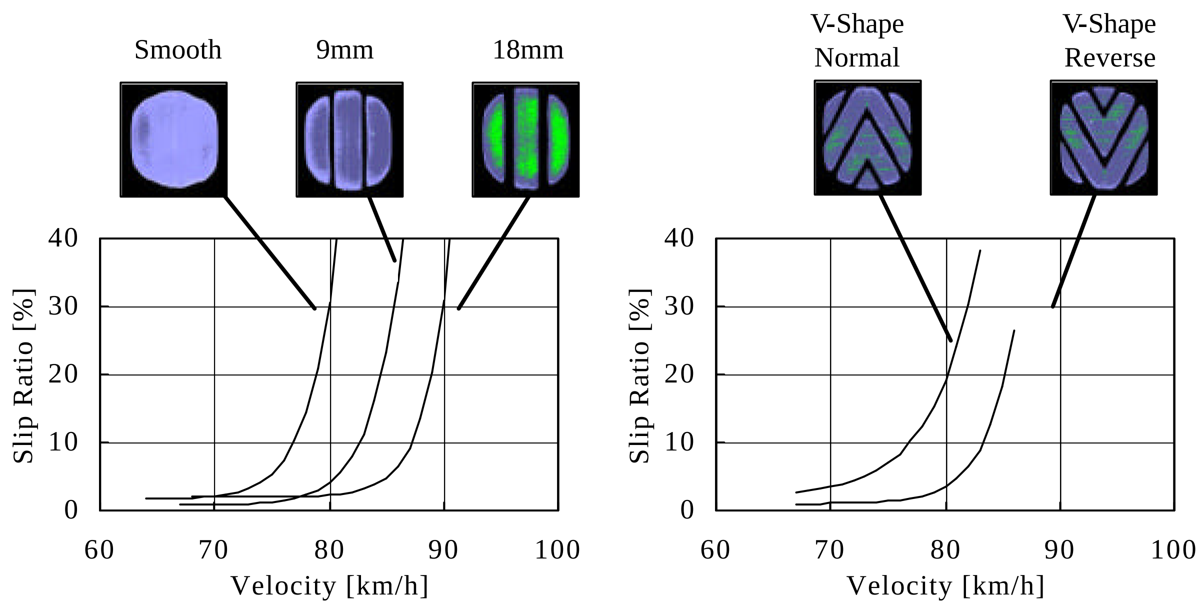

Figure 8. *Experimental results of hydroplaning test*

When vehicle velocity exceeds a critical velocity, slip ratio of tire rises drastically by the onset of hydroplaning. "Experimental hydroplaning velocity" is defined here as a vehicle velocity at which slip ratio reaches 10%. Hydroplaning velocity for the wide grooved tire is the highest, narrow grooved tire is the second, followed by the smooth tire. For V-shaped groove tire, hydroplaning velocity in normal direction rotation is higher than the reverse direction. Thus the effect of with/without straight grooves and also the effect of rotational directions of V-shape groove tires are well captured by the experiments.

Verification for A Smooth Tire and A Longitudinal Grooved Tire

Hydroplaning simulation of a smooth tire and a tire with longitudinal grooves are carried out first, as shown in Figure 9. To simplify the computation, tire and fluid are analyzed by half-model, dividing into right and left portions by taking advantage of geometrical symmetry. Tire stands still with the rated inflation pressure and vertical load. Total numbers of elements of a smooth tire and fluid are 10,170 and 66,550 respectively.

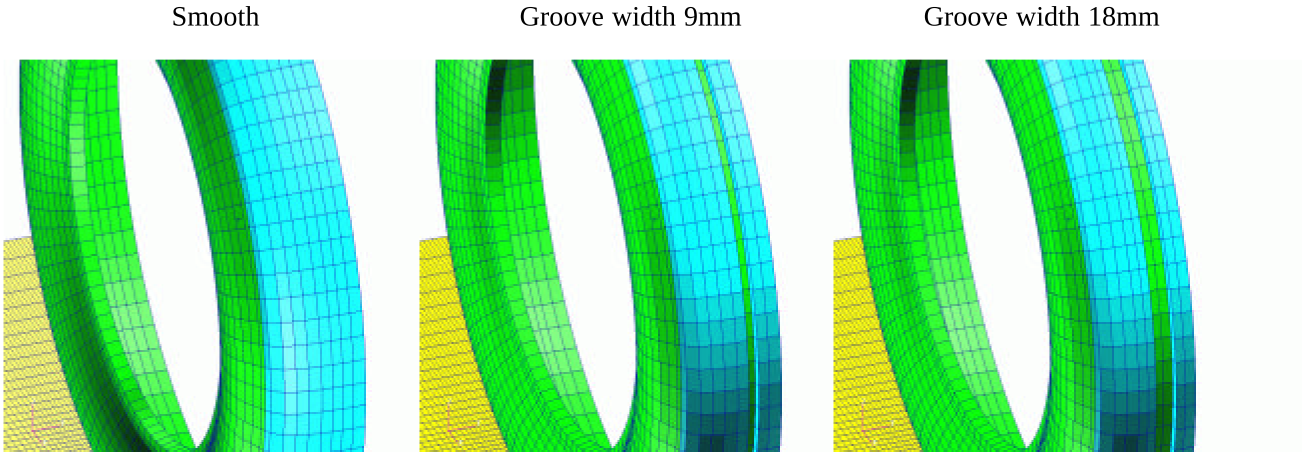

Figure 9. *Models of longitudinal grooved tire*

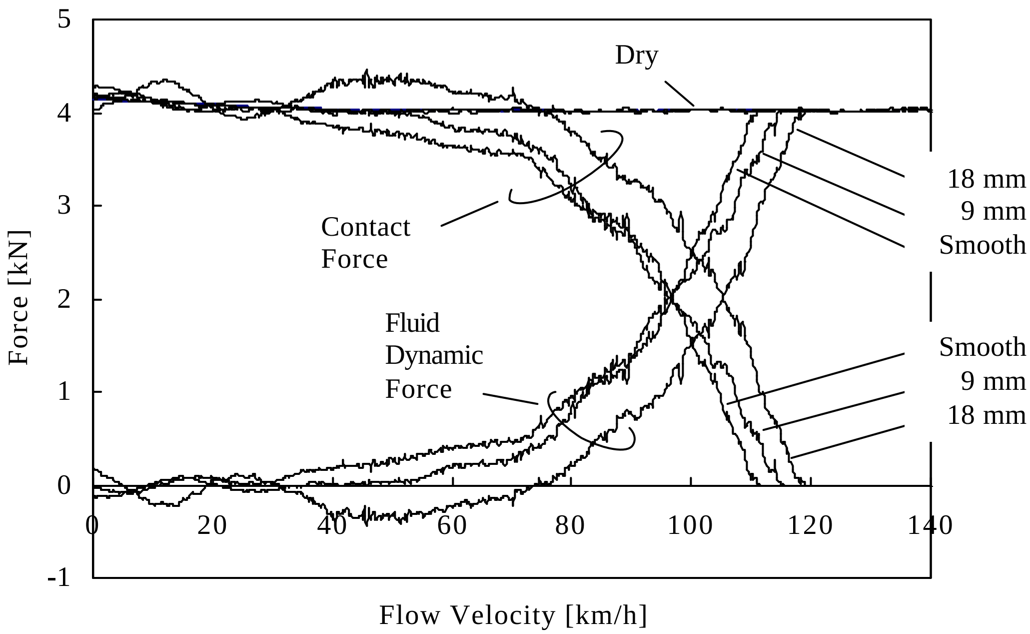

Figure 10. *Velocity dependency of contact force (longitudinal grooved tires)*

Figure 10 represents the contact force variations between tire and road, when the fluid velocity varied. In the same figure, contact force on dry road condition is also shown where influence by the water fluid does not come into play. The fluid force, which causes hydroplaning, is computed as the contact force difference between the case in which coupled problem are not considered, and the case in which coupling are considered. The fluid force increases as fluid velocity increases. The hydroplaning velocity for the widely grooved tire is the highest, with narrow grooved tire second, and followed by the lowest smooth tire. Clear observations can be made that the effect of the with/without longitudinal grooves as well as the groove width.

Next, above simulation results are compared with experimental results obtained at proving ground. Figure 11 indicates the good correspondence of the predicted hydroplaning velocities of smooth tire, narrow grooved tire and wide grooved tire, with the experimental counter parts. Figure 12 indicates the water flow of 80km/h around tire contact area. Flow behavior around tire contact area and also water jet extrusion from longitudinal groove can be clearly observed. These observations well correspond to the experimental visual images at proving ground. Water jet exhausted from the groove and other things are impressively captured.

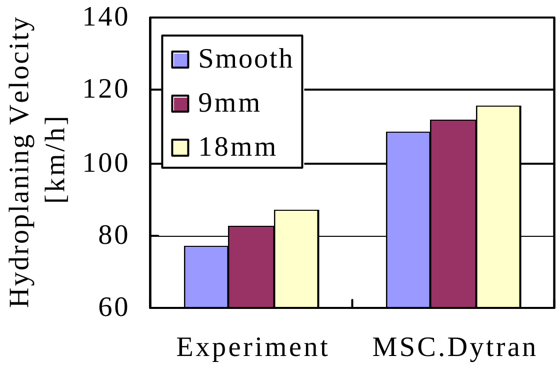

Figure 11. *Comparison of hydroplaning velocity (longitudinal grooved tires)*

Verification for A V-shape Groove Tire

Next, as shown in Figure 13, rotational directions of normal and reverse senses are investigated for V-shape grooves. Here, tires are rotated, by first rated inflation pressure and vertical tire load are applied and then applying transverse velocity to the road. Also, inertia force is applied to the fluid, to generate the same velocity as the road. Total number of elements of the tire with V-shape grooves and fluid is 31,332 and 133,100, respectively.

Figure 14 represents the contact force variations between tire and road, when V-shape grooved tire rotates. Fluid dynamic force increases, as fluid velocity increases. Contact force for the reverse rotation diminishes to zero at lower velocity than the normal rotation, which indicates that the tire is completely lifted above the water layer.

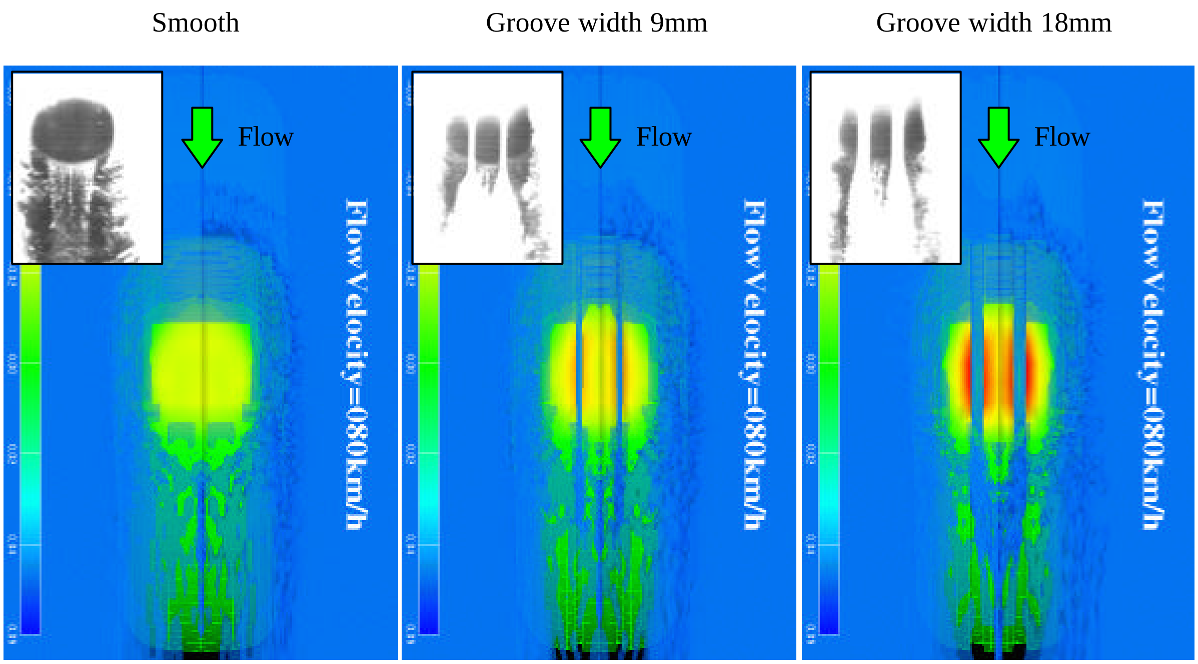

Figure 12. *Bottom view of water flow (longitudinal grooved tires : 80km/h)*

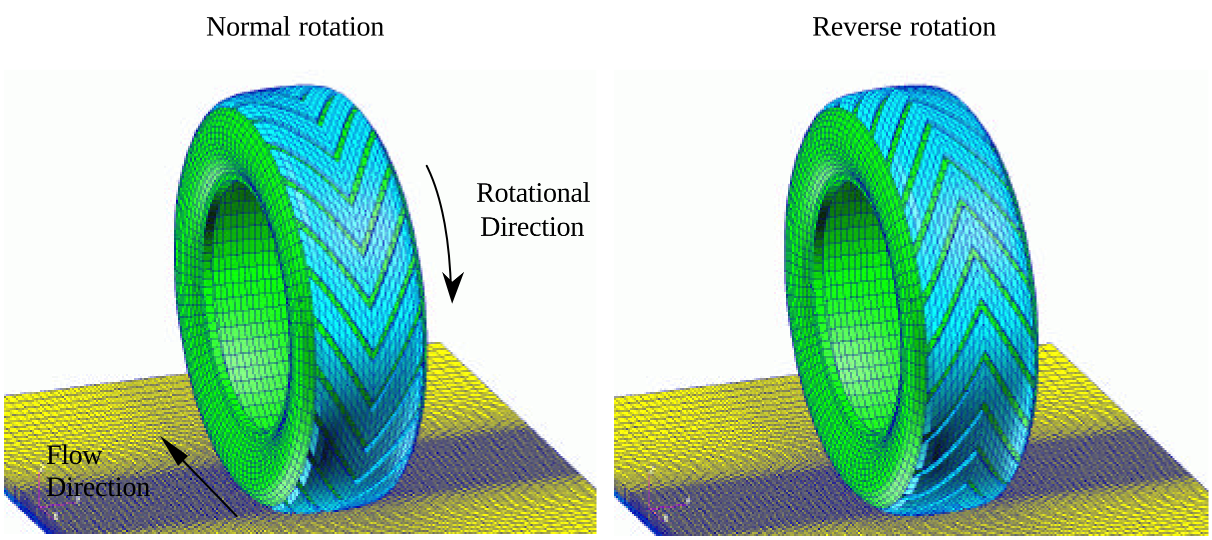

Figure 13. *Models of V-shape grooves*

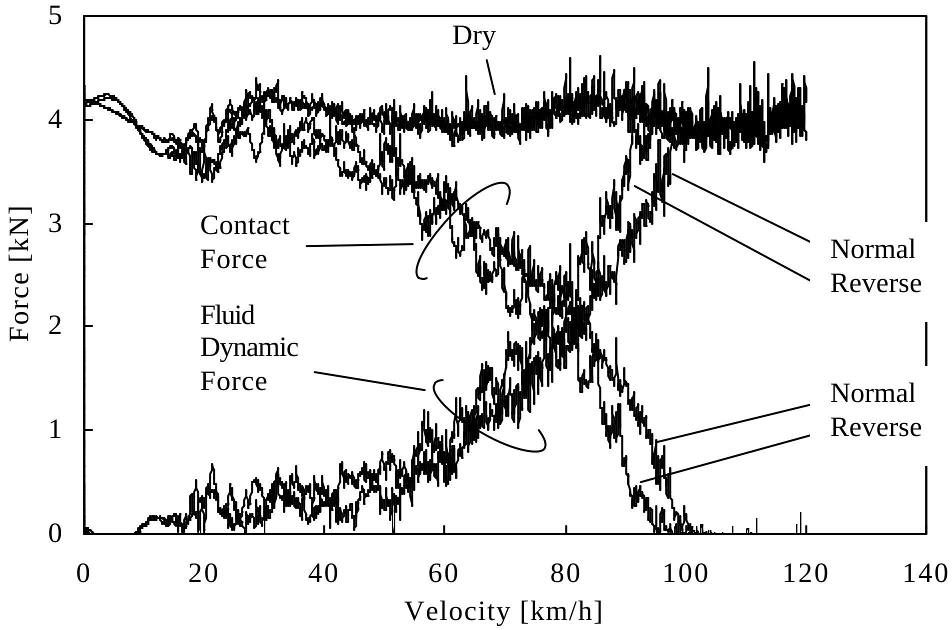

Figure 14. *Velocity dependency of contact forc(V-shape grooved tires)*

Numerical results are compared with experiments. Figure 15 indicates the good correspondence between predicted hydroplaning velocity of V-shape grooved tires and experiments.

Figure 16 show the intrusion process of water wedge comes into the interface. Simulation results indicate that the water wedge intrudes into the contact area gradually, as fluid velocity increases. Contact patch of a tire is completely covered with water, when velocity reaches 120 km/h. Especially in the high-speed region over 80km/h, water wedge begins to intrude from around the center of the leading edge of the contact patch. In more high-speed region, water wedge spread out in left side and right side in the contact patch, and finally, all region of contact patch floats on the water film completely. Since this tendency is remarkably observed in reverse rotation than the normal rotation, the present numerical procedure is thought to be able to predict transient hydroplaning phenomenon.

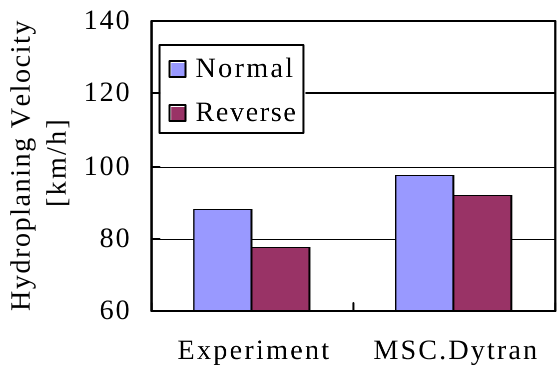

Figure 15. *Comparison of hydroplaning velocity (V-shape grooved tires)*

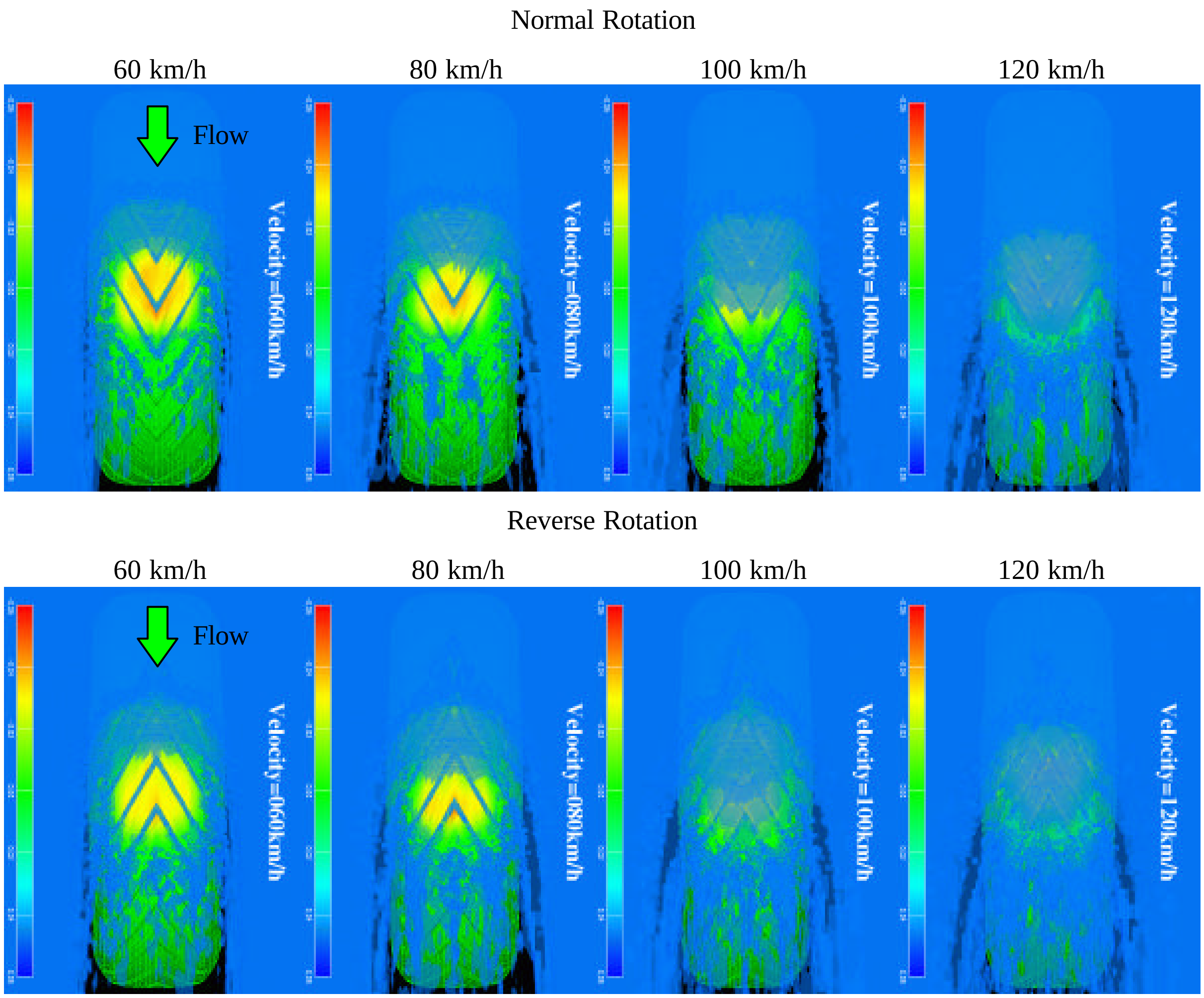

Figure 16. *Intrusion Process of Water into The Contact Patch*

Numerical Example

Lastly, as the numerical example of the newly developed prototype tires, whose tire size are 215/45ZR17, are chosen and analyzed for the normal and reverse directional rotations. Specifications of tires are, vertical load: 4kN, and inflation pressure : 200kPa.

Figure 17 indicate FEM model of tire, tread pattern, and FVM model of water layer, respectively. Total number of elements of a tire with tread pattern and fluid are 29 760 and 254 800, respectively.

Figure 18 indicate more extruded water flow at the front edge of the contact, when rotational direction is reversed. Regarding water flow intruded into the contact patch, here also, more water flows into the contact patch when tire rotates to reverse direction. It is understand that the hydroplaning performance of the reverse rotation is inferior to the normal rotation.

Above discussion leads to the conclusion that the present numerical method is also applicable for the developed tires with complex tread pattern geometry. The present method enables the visualization of water flow drained by complex tread pattern, which has been a difficult task in the past.

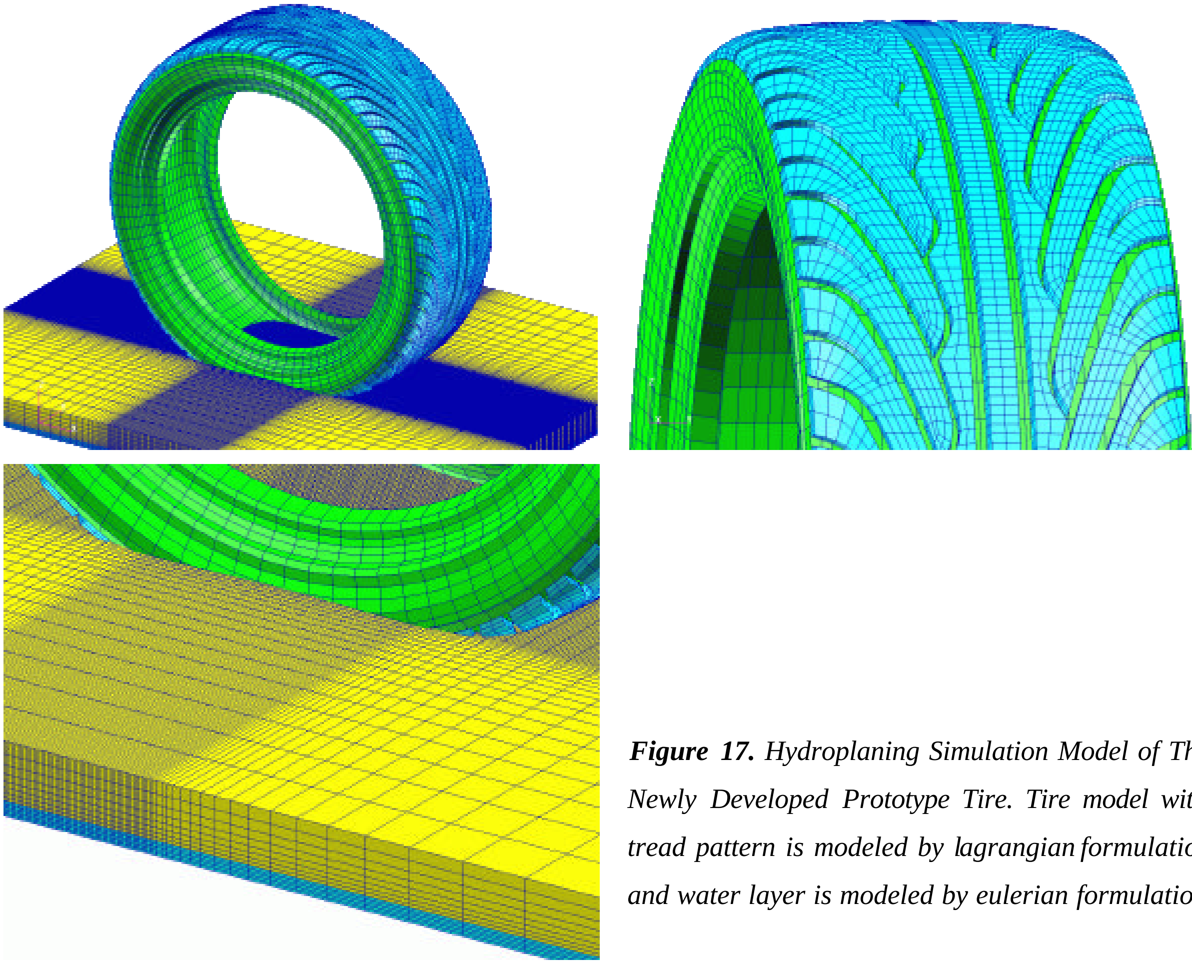

Figure 17. *Hydroplaning Simulation Model of The Newly Developed Prototype Tire. Tire model with tread pattern is modeled by lagrangian formulation and water layer is modeled by eulerian formulation.*

CONCLUSION

Numerical method for predicting the onset of hydroplaning velocity, which is an important index of hydroplaning performance of a tire, is proposed by the computation of velocity dependence of the contact force between tire and road, using MSC.Dytran. To verify the effectiveness of the method, predicted hydroplaning velocities for four different simplified tread patterns are compared with experiments. It is confirmed that results agree well with each other. Furthermore, predicted water flows around contact patch area agree well with the observation made by the video. These agreements are thought to support the effectiveness of the present hydroplaning simulations.

As a result, new numerical procedure proposed here enables to predict the process of the hydroplaning of a tire and the difference of the hydroplaning performance dependent on the effect of the tread pattern and its geometry quantitatively.

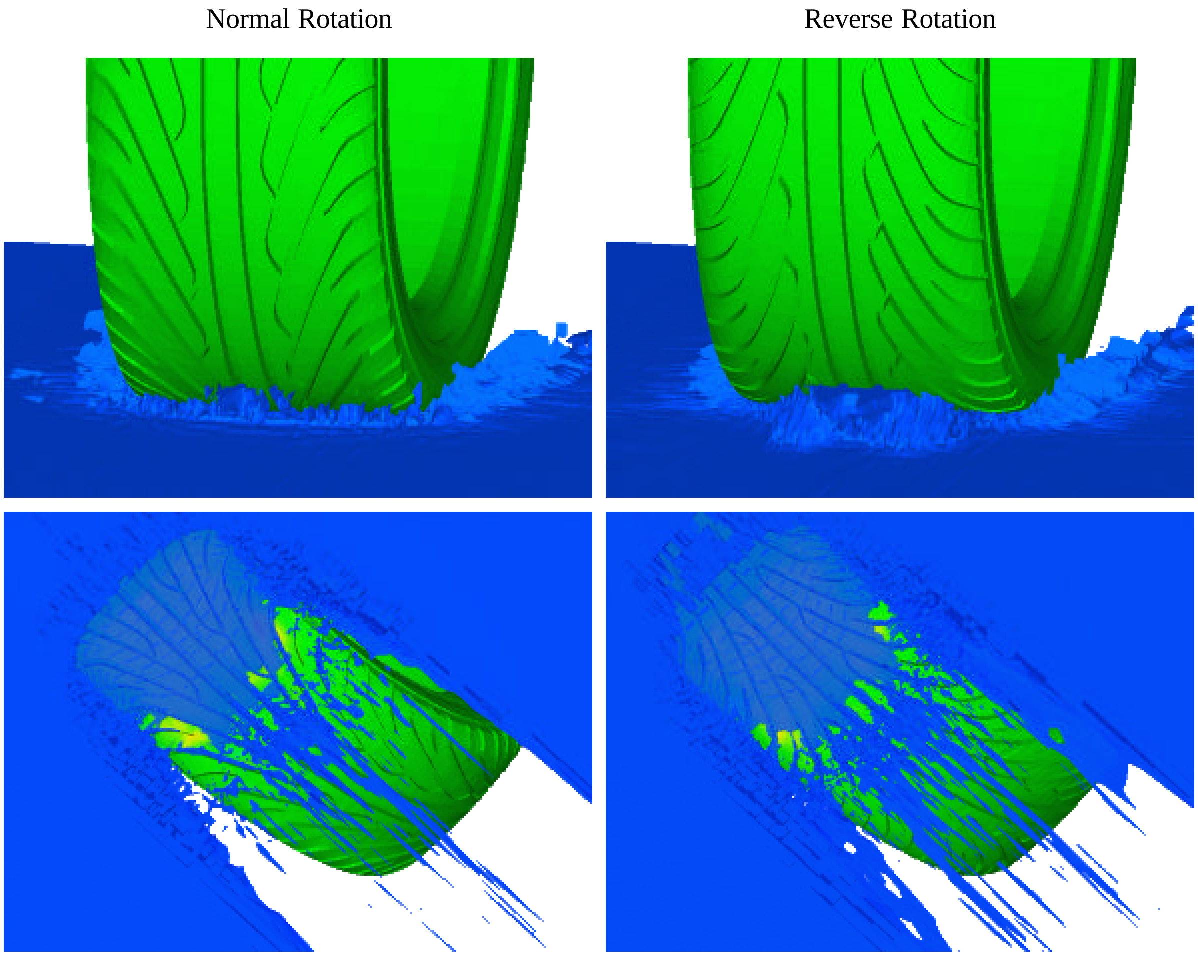

Figure 18. *Computational Results of The Newly Developed Prototype Tires (80km/h).*

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