

A Study of the Ditch Fall-over Test Method Using Numerical Simulation

Tatsuya Fukushima, Masafumi Shitamichi, Osamu Nishikata, Masamitsu Mori, Keiji Hatano and
Toshikazu Torigaki
Nissan Motor Company Ltd.

Masato Nishi and Takahiko Miyachi
JSOL Corporation

ABSTRACT

Rollover tests are performed to design the algorithms for deployment of countermeasures to mitigate occupant ejection in rollover situations. The ditch fall-over test is one of the rollover test methods in which a vehicle on a steep slope, representing a ditch embankment, is subjected to a forced steering operation that results in a turnover. An accurate prediction method is needed to determine the specifications of the ditch fall-over test equipment and test conditions because a test-based trial-and-error process involves high cost of performing repeated experiments and preparation for various types of related test equipment.

This paper presents a newly developed numerical simulation method for simulating vehicle behavior in ditch fall-over tests. The vehicle model used in the simulation incorporates a finite element tire model for calculating the contact forces to a steep slope in a rollover situation characterized by large contact patch deformation with very large camber angles relative to the slope, an operating condition that ordinary vehicles cannot handle. The vehicle model also includes the suspension systems, steering system and inertial properties of the vehicle. Under various test conditions, the simulation results agreed well with those of actual ditch fall-over test data to judge whether turnover occurred or not and also the dynamic response such as vehicle roll rate. Simulations were conducted to investigate the test equipment specifications and test conditions for a vehicle. It was found that the slope angle, the friction coefficient of the slope, initial vehicle velocity and the sectional shape of the slope at the top influence vehicle turnover behavior.

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INTRODUCTION

A system for preventing occupant ejection through a side window in a rollover crash will become mandatory from Sept. 2013 in the United States under Federal Motor Vehicle Safety Standard (FMVSS) 226-Ejection Mitigation. Inflatable side curtains are among the occupant restraint systems that could be deployed in a vehicle rollover to prevent occupant ejection through a side window. In this case, it is necessary to detect vehicle dynamic behavior and judge whether the vehicle is likely to overturn or not. If a rollover is deemed imminent, the occupant restraint system will then be activated. In order to determine the conditions for judging the likelihood of a rollover, tests must be conducted to measure vehicle rollover behavior. Since FMVSS 226[1] does not specify any particular rollover test method, vehicle

manufacturers and occupant restraint system suppliers have to establish a vehicle rollover test method by themselves.

The U.S. National Highway Traffic Safety Administration has classified various types of vehicle rollover modes based on dynamic behavior as shown in Fig. 1, according to the different rollover patterns displayed in rollover accidents in the past. These different types of rollover modes must be reproduced experimentally in order to determine the conditions for activating occupant restraint systems in rollover accidents corresponding to each rollover pattern. Based on the results, the conditions for activating occupant restraint systems to prevent occupant ejection in the rollover patterns shown in Fig. 1 must be defined.

One type of rollover test is a ditch fall-over test[2,3] as shown in Fig. 2, which corresponds to the fall-over type of rollover accident. In a ditch fall-over test, a vehicle traveling

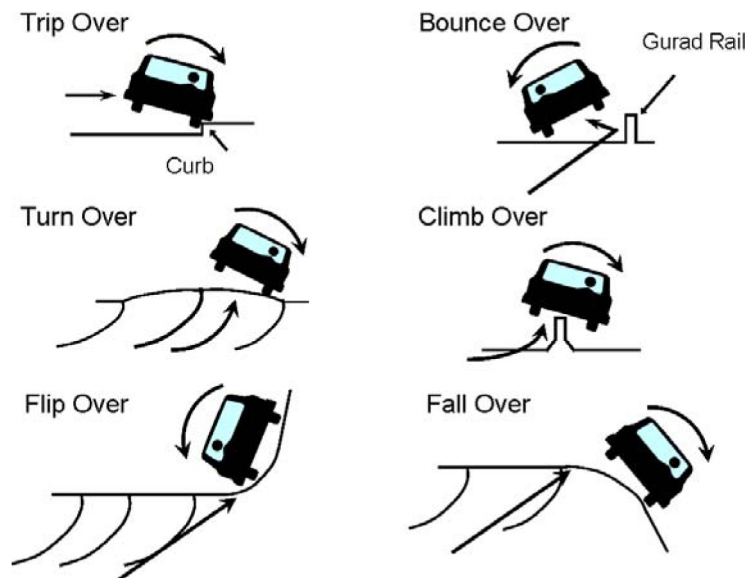


Figure 1. NHTSA (NASS-CDS)'s classification for Rollover initiation types



Figure 2. Ditch fall-over test

straight ahead leaves the flat roadway and enters the ditch slope. Subsequently, the vehicle turns over as a result of a steering maneuver by the driver to turn the vehicle so that it runs up the ditch bank. The vehicle rolls over in this test because the reactive force of the tire lateral force, produced by the steering maneuver to turn the vehicle upward while it is traveling along the slope, acts on the vehicle as a moment to roll it over down the ditch. In order to determine the conditions for activating the occupant restraint systems in a ditch fall-over test, vehicle dynamic behavior on a ditch slope must be measured in both rollover and non-rollover situations. The roll moment acting on the vehicle can be cited as one of the first factors affecting the behavior of a vehicle that rolls over in a ditch fall-over test. The roll moment are caused by the lateral force produced by the tiresensor. The elements related to these forces acting on the vehicle are the friction coefficient between the tires and the slope and the slope angle. In addition, since the tires do not produce lateral force unless they slip, a roll moment due to lateral force does not occur unless there is a steering maneuver that induces tire slip for lateral direction of itself. The friction coefficient between the tire and the slope decides an upper limit of the lateral force that tire produces. Therefore, the magnitude of a roll moment that acts on the vehicle due to the lateral force

produced by the tires is presumably strongly influenced by where and how fast the driver executes a steering maneuver on the slope. Moreover, variation in a roll moment due to the magnitude of the vehicle velocity at the time it enters the slope cannot be easily estimated.

As mentioned above, FMVSS 226 does not specify a rollover test method for detecting a vehicle rollover event. Accordingly, manufacturers have to establish the conditions of the ditch fall-over test or other similar test for determining the safety equipment deployment conditions. Unless one is capable of predicting accurately the vehicle dynamic behavior relative to the slope angle, tire-slope friction coefficient and the steering maneuver on the slope in a ditch fall-over test, it is quite difficult to determine the necessary test conditions for inducing or not a rollover with certainty. Attempting to identify the conditions by trial and error in ditch fall-over tests would require the preparation of various types of large slopes and many test vehicles. Because of the costs and time required, that would not be a realistic way of defining the test conditions. Therefore, we have developed a numerical simulation method for predicting vehicle behavior in ditch fall-over tests. This simulation method was then used to examine the test conditions for the ditch fall-over type of vehicle rollover.

NUMERICAL SIMULATION METHOD

(a). Overview

Changes in vehicle behavior in ditch fall-over tests due to the use of different values for various test conditions must be investigated accurately. In order to estimate vehicle dynamic behavior as accurately as possible, it was decided to conduct a dynamic structural analysis of vehicle behavior using the non-linear finite element method because the motion of a vehicle undergoing rollover, consist of strong non-linear phenomenon such as accompanied by large deformation of the tire. Fukushima et al. [4] developed technique to simulate the Vehicle Cornering and Braking Behavior in extreme condition using a finite element method. They applied this simulation technique to rollover simulation. Numerical simulations were performed using the LS-DYNA[5] general-purpose explicit finite element program for non-linear dynamic problems. Finite element (FE) models of the vehicle were created for use in the simulations. The ditch slope was also created as a rigid wall in the simulation. In a vehicle crash simulation, the numerical calculation of the deformation of the entire vehicle is targeted at phenomena that occur in approximately 0.1 s, whereas the numerical simulations for a rollover event treat phenomena that last for 4-5 s. Accordingly, that would require approximately 50 times as much computational time, if a FE model of crash simulation is applied to a ditch fall-over situation. Therefore it would not be a realistic way of investigating the test conditions with a crash simulation model. Therefore, it was decided not to model items that are not measured in a ditch fall-over test, so as to allow the degrees of freedom of the vehicle model to be reduced and the time step size of time integration to be expanded. The most effective way of shortening the computational time is to represent the vehicle's body as a rigid body. Since the object of a ditch fall-over test is to measure vehicle behavior, vehicle body deformation caused by the rollover is not evaluated. Therefore, the vehicle body supported by the suspension system, engine, drive-train and interior parts were all integrated into one rigid body model. The inertial properties of the portions supported by the suspension system, i.e., the position of the vehicle's center of gravity, mass and inertia tensor value, were input directly into the rigid body model based on the design values or experimentally measured values.

(b). Vehicle model

It was assumed that the links making up the suspension system do not deform much in ditch fall-over tests. The factors influencing vehicle behavior here are mainly limited only to the lateral force between the tires and the slope and the gravitational force, both of which are approximately equal in magnitude. Accordingly, the deformation of the suspension links was ignored, and the links were represented as rigid bodies. However, in ditch fall-over tests, the suspension

springs undergo pronounced contraction or expansion at the time the vehicle leaves the flat roadway and enters a slope with a steep angle as well as when the vehicle rolls over. Moreover, the vehicle is steered in the direction to run up the slope while traveling along the ditch bank. For these reasons, the properties of the joints connecting the suspension links and the rubber bushings were modeled so that the operation of the suspension system could be simulated. The springs, shock absorbers, rubber bushings and other parts related to the operation of the suspension system were modeled using one dimensional discrete elements incorporating the respective part properties for the purpose of reducing the degrees of freedom of the vehicle model and lengthening the time integration interval.

In ditch fall-over tests, the tires undergo large deformation that substantially influences vehicle behavior because major force to the suspension systems are gravitational force and the friction force between the tires and the slope. The actual tire shape and structure were faithfully represented in an FE model in order to calculate the large tire deformation that occurs in the ditch fall-over situation. The tire model has the capability to simulate rolling motion and produce lateral force according to the pressure distribution on the contact patches and friction coefficient defined between the tires and the slope. The vehicle model composed of the afore-mentioned elements is shown in Fig. 3. The outer body shell parts colored in grey and the black bar elements have no inertial mass. This outer body parts are for visualizing the motion of the body straightforwardly. The rigid black bar elements are included in a rigid body to mount the suspension system, the steering system to this rigid body at the ends of bar elements. They follow the rigid body motion suspended by the suspension systems. As is clear from the figure, the calculation of the deformation of the tires, which faithfully model the actual tire shape and structure, accounts for most of the computational cost incurred in using this vehicle model in a numerical simulation of a ditch fall-over test.

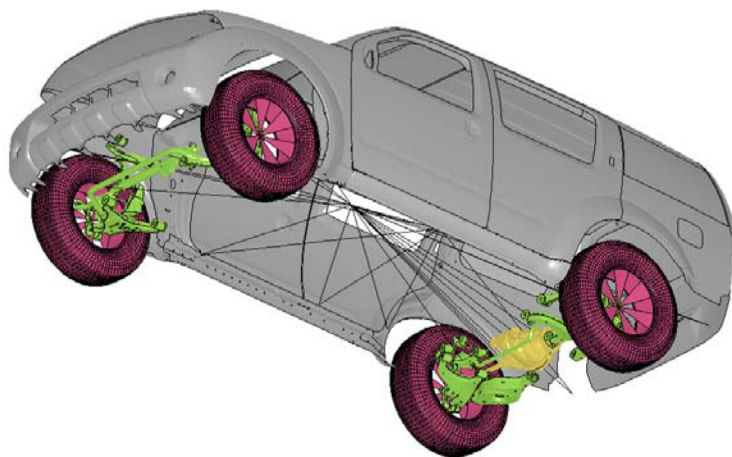


Figure 3. Vehicle simulation model

(c). Simplified tire model with enough stability to simulate vehicle ditch fall-over

The lateral force produced by the tires determines the vehicle behavior until rollover occurs in a ditch fall-over test. Tire lateral force is influenced by tire deformation, and in a ditch fall-over test the vehicle travels at very large camber angles relative to the slope such that the sidewalls touch the ground until the time when rollover occurs. Tires experience deformation that is not likely to occur in normal driving situations. The tires were represented in an FE model because it was posited that by faithfully expressing the tire shape and structure, the tire lateral force produced under a condition of sidewall contact with the ground could be reproduced in a numerical simulation of a ditch fall-over test. [Fig. 4](#) shows the FE tire model used in the numerical simulations.

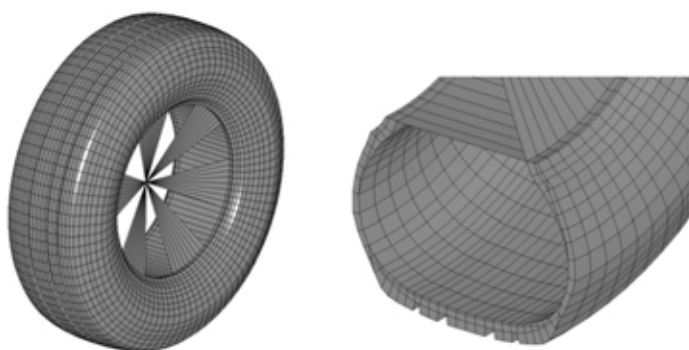


Figure 4. FE tire model

The tire model in [Fig. 4](#) is composed of approximately 20,000 elements and the elements are segmented such that the time integration interval is at least 1.0 μ s, making it possible to calculate in a short period of time phenomena that last for several seconds. One measure taken to develop this simplified tire model is that only the longitudinal grooves of the tread pattern were modeled. If the tires are modeled with a small number of elements for the purpose of shortening the computational time, the size of the solid elements used to represent the rubber material at the contact patch becomes larger. In a situation like a ditch fall-over test where large lateral forces are generated leading to a rollover, the tire contact patch is skewed toward the edge of the tread face and the sidewalls come in contact with the ground. Such tire deformation does not occur in ordinary driving.

Excessive strain is produced by the transverse shear force that occurs in the solid elements representing the rubber material at the tire contact patch. That results in hourglass deformation leading to distortion of the mesh as shown in [Fig. 5](#). This tire deformed unrealistically is mounted at right and front wheel of a vehicle under one of the roll over conditions of a ditch fall-over test. The bright-appearing elements in the figure are the contact patch which sits astride the tread and the side wall. The portion with the wavy hourglass deformation running in the direction of tire rotation is the interface between the tread face and the sidewall. This

pronounced hourglass deformation can distort the brick elements and make it impossible to continue the calculation. Even if the calculation can be continued, the calculated lateral force does not have enough numerical accuracy to simulate the vehicle's rollover motion. This hourglass deformation that occurs at the contact patch is a phenomenon unique to numerical simulations and is caused by reduced integration of element and large mesh size. This type of deformation does not reproduce the deformation exhibited by an actual tire contact patch. In this study, hourglass control was used to produce an artificial reactive force within the range that did not appreciably affect the deformed shape of the contact patch at the brick elements of rubber materials. This control measure suppressed mesh distortion induced by hourglass deformation at the contact patch. The type 7 hourglass control in the LS-DYNA program was used in the simulations to suppress hourglass deformation induced by deformation of the tire rubber under large strain, and it had little effect on the tire lateral force[6]. This type 7 hourglass control applies two hourglass control schemes, stiffness and viscous, in parallel. [Fig. 6](#) compares the lateral force F_y calculated with the tire model created using the modeling technique explained here and the results of a bench test conducted with a flat belt tire tester. The lateral force characteristics obtained with the tire model have good agreement with those of the actual tire with respect to the slip angle and the perpendicular force to the road surface.

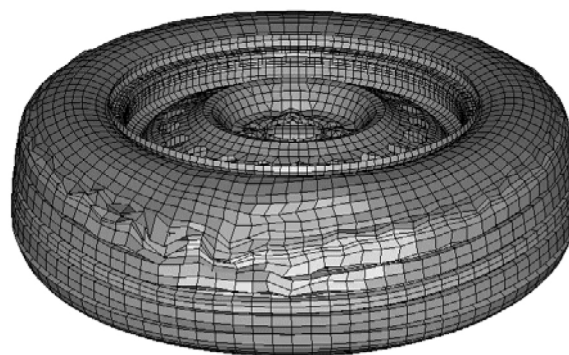


Figure 5. Distortion of tire tread surface mesh due to hourglass deformation

(d). The way to perform ditch fall-over simulation

The slope used in the simulation of a ditch fall-over test was modeled as a rigid wall, and the tire-slope friction coefficient was applied according to the definition of contact with the tire model. Contact between the tire model and the slope was defined at the tire tread face and the sidewall. The friction coefficient between the sidewall and the slope was set smaller than that between the tread face and the slope similar to actual tires. When using the vehicle model shown in [Fig. 3](#) to conduct a numerical simulation of a ditch fall-over test, the friction coefficient between the tires and the slope is an