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The Effect of Steering Effort on the Simulated Rollover Dynamics Behavior of Cars

Lee Yoonsu

George Washington University Online High School, 44983 Knoll Square, Room 153, Ashburn, VA, 20147, U.S.A.; yoonlee9302@gmail.com

ABSTRACT: This study proposes the threshold level of steering effort to reduce rollover accidents. There is much research about the causes of rollover behavior during driving. The center of gravity height, tread length of road wheels, tire properties, and ESC is among the leading causes of rollover of vehicles. An enormous amount of research was done on those factors. First, the steering effort threshold value, which leads to loss of wheel grip, was tested. Second dynamic maneuver tests were done in a virtual environment with the help of CarMaker® vehicle dynamics software. By doing that, steering effort could be measured to understand how much effort is needed in those risky situations.

KEYWORDS: Rollover; steering effort; vehicle dynamics; cars.

Introduction

Rollovers are a type of collision in which a car tips over to its side or roof, runs off the road, and has a more severe fatality rate than other crashes. SUVs and pickup trucks have a higher tendency to roll over. Many factors in vehicle design affect this phenomenon, but the center of gravity height or wheel tread length is the leading cause of this problem. A National Highway Traffic Safety Administration (NHTSA) report in 2019 describes that the rollover rate of SUVs in fatal crashes was 21.2%. This rate exceeds the rollover rates in fatal crashes of all other common types of motor vehicles: cars, pickup trucks, vans, large trucks, and buses.[1] This higher fatality rate makes rollovers the main culprit of most deadly accidents. This phenomenon occurs in two ways. One is the collision-induced rollover, and the other is the steering input-induced rollover. These two rollovers are closely related to SUV vehicles' characteristics. This propensity to rollover could be better avoided if better-designed and tuned dynamics of the vehicles are sought and developed. The usual tuning guide to deviate this propensity in vehicles is the lessening of steering effort and the ESC (Electronic Stability Control) modification, which reduces human effort and stabilizes the behavior in tipping points of rolling over. Sivinski says, "as ESC saturates the on-road fleet in the coming years, it is likely that rollovers resulting from loss of vehicle control will continue to decline. Other types of rollovers, such as those caused by an impact with another vehicle, are not likely to be affected by the spread of ESC in the population."[2] The studies about ESC and vehicle control systems are more abundant than steering ones.

On-road rollovers due to vehicle maneuvering comprise only a tiny percentage of rollover crashes. Still, despite its small percentage, significant importance is given to steering input-induced problems for safety reasons.[3] So the objective of this study is to highlight the importance of the role of the steering system in risky maneuvers like J-turn or double lane change, which are the recommended tests for rollover validation.

For this study, a special bench test was prepared with the help of Halla University's car lab. Real steering threshold effort could be measured based on this; a practical virtual method was employed to prove this threshold value.

1.1 Technological background for simulation test:

Actual tests for dynamic maneuvers are dangerous and challenging to implement on normal roads because of traffic. And most developers of vehicles use a proving ground which is specially developed roads and environments for vehicle testing. Because it is safe and efficient for this kind of test, another way of doing a dynamic maneuver test is a simulation, which uses a vehicle, road, and driver in a mathematical model and evaluates the car in various maneuvers. Mostly the simulations are done in a completely virtual environment, but a valuable way of using simulations is to combine them with physical models. This is called a HIL (Hardware In the Loop) simulation. This makes the test more reliable and realistic. Because the interesting parts are real and don't need to be modeled in mathematical form, this study used steering gear as hardware, and the signals from the gear go to the virtual car model and steer the car. And the car model calculates the road wheel force and pushes or pulls the steering gear by the Hils actuator; in this way, they interact with each other.

Pfeffer and Koegeler developed the steering system HILS test with European car makers, and by using this method, they optimized the tuning map of the steering system to get the best steering feel and characteristics.[4,5]

The research about the virtual driver model is various. Most apply to everyday situations where the vehicle doesn't skid on the path due to an unavoidable slip angle. But some research on vehicle dynamics dealt with tire dynamics and driver behavior at the limits of handling, from lane keeping to drifting.[6,7] This discussion can be expanded to vehicle safety systems to avoid accidents effectively by taking the physical limitations of vehicles into account. To repeatedly evaluate a vehicle control system in the same situation, simulations with a suitable driver model are needed to provide reliable analysis results and satisfy cost and safety issues, especially at the limits of handling.

■ Methods

Equipment for steering effort measurement:

The equipment was used to test components and systems without requiring a complete vehicle. The steering wheel was connected to the input test actuator, and steering gear ends were connected to the two output test actuators. The simulation was the same as running offline in CarMaker®, but the real components were used instead of the software's steering model. Figure 1 shows the method used to measure the effort of grip loss and its bench and equipment.

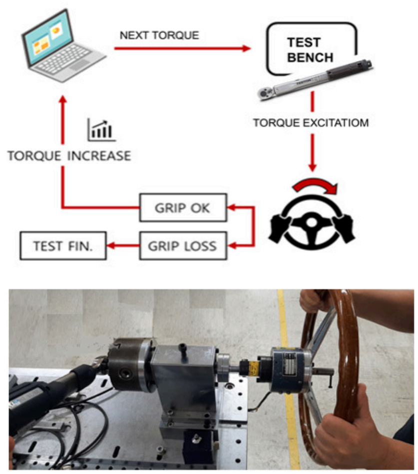

Figure 1: Schematic diagram and test equipment.

HILs dynamic maneuver test:

Rigs were used to test components and systems without requiring a complete vehicle. The steering wheel was connected to the input test actuator, and two tie rod ends were connected to the road wheel actuators. The simulation was the same as running offline in CarMaker®, but the real components were used instead of the software's steering model. And a standard SUV model was chosen for this study (Figure 2).

The steering torque is closely related to rack force, calculated by rack position, velocity, and acceleration. To control the vehicle's direction, the natural rack motion quantities were inputted to the vehicle simulation model by the rack motion feedback mechanism installed on the test bed.

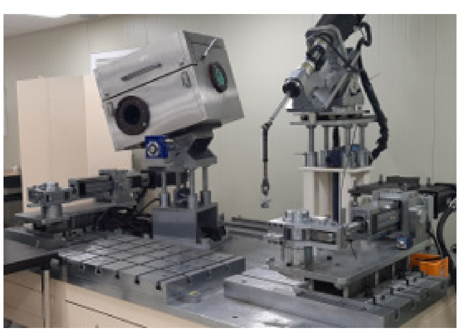

Figure 2: Steering HILS equipment (1 input /2 output actuator).

Most of the dynamic maneuver test covers open loop tests like steady state circular (ISO 4138), sine sweep (ISO 7401), and weave test, which doesn't require a driver's role in the test. But most subjective tests conducted in the proving ground were closed loop tests like ISO Lane change (ISO3888) or slalom and handling courses. The standard driver model was installed in the software to simulate the closed loop test on the HILS benches. Figure 3 shows closed loop test principles which feedback the vehicle response to the driver tasks.

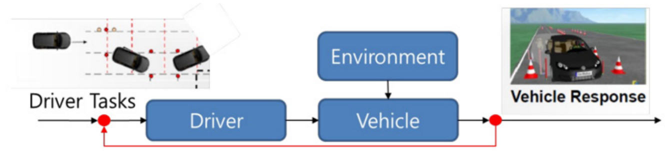

Figure 3: Closed loop test principle.

The experiment on Steering grip loss and the result:

A special test rig was devised to see the threshold of steering effort that makes a driver lose grip of a wheel. The test procedure was as follows: Evaluator generated the torque-based excitation by using a torque meter manually, and the evaluatee stood behind the wheel. The evaluator increased the torque until the evaluatee lost grip of the wheel and recorded the value. The grip loss effort was defined as the torque that makes one lose one's grip on the wheel and let the wheel rotate 60 degrees. This study selected 5 participants who could represent the age group between 18 and 60. And 20 tests were conducted for each person, and the threshold values were averaged. Figure 4 shows the distribution of these efforts and has a normal distribution.

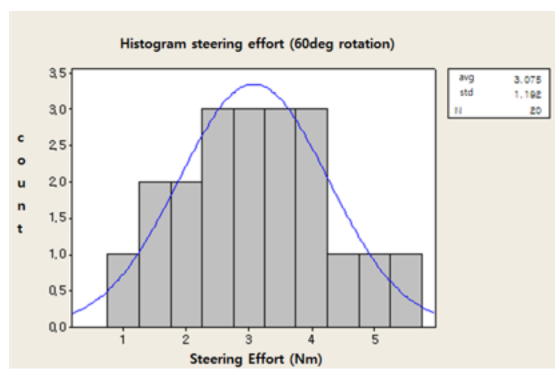

Figure 4: Histogram of grip loss effort.

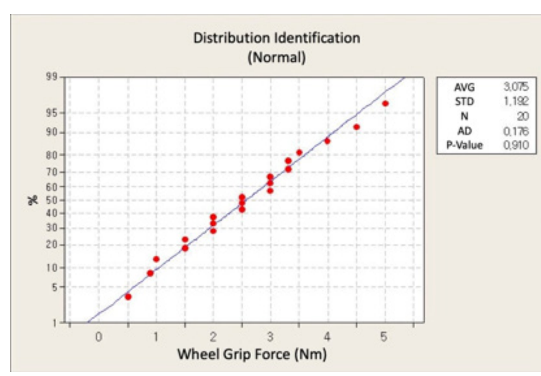

Figure 5: Distribution Identification.

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The p-value is a probability that measures the evidence against the null hypothesis. For an Anderson-Darling test, the null hypothesis is that the data follow the distribution. Therefore, lower p-values provide more substantial evidence that the data do not follow the distribution. P-values greater than 0.05 and Anderson-Darling statistic is small enough to conclude normal distribution. Most importantly, the average effort of grip loss was 3.075 Nm. And this shows that the effort that exceeds this value could make the driver lose control of the car and lead to a rollover.

High-risk dynamic maneuver test

Index development for dynamic maneuver test:

To be able to compare outputs from complete simulation and HILS tests in an objective way, key indexes were used. Indexes are effective since the behavior of the data is described in a scalar value, making it easier to compare. So, the most traditional and commonly used rollover index was defined using a 2D vehicle model as

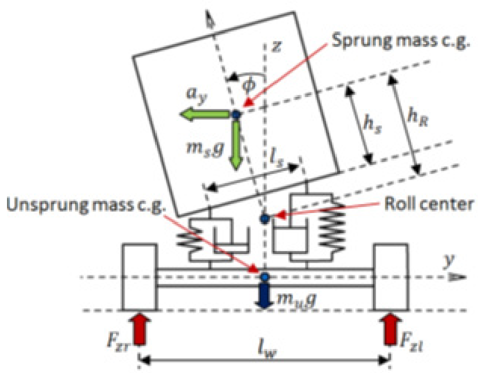

Figure 6: Rollover diagram in a 2D car model.

they are shown in Figure 6. Several researchers tried to invent a new rollover index for tripped rollover from external inputs such as forces.[8] But this study confines the rollover in the high lateral acceleration-induced rollover category. The formula is LTR (Load Transfer Ratio) in Equation (1). When the vehicle is lifted and the tire is off the ground, the vehicle could be said to have rolled over. The main parameters of the rollover index LTR are lateral acceleration a_y and roll over angle ∅ and the vehicle is said to be rolled over when LTR-value nears 1.

$$R = \frac{F_{zr} - F_{zl}}{F_{zr} + F_{zl}} = \frac{2m_s a_y h_R}{mgl_w} + \frac{2m_s h_R \tan\emptyset}{ml_w} \quad (1)$$

Where

F_{zr} F_{zl} = Left, Right-hand Tire Forces in the Z direction

M_s = sprung mass

h_R = Radius of sprung mass rotation for R.C

l_W = wheel tread distance

a_y = lateral acceleration

Test maneuvers

Double Lane Change:

Pylons were arranged as seen in Figure 7 and Figure 8. The test consisted of an entry and an exit lane with a length of 12m and a side lane with a length of 11m. The driver factor is the most influential in this test; objective results couldn't be anticipated in the past. Vehicle speed for this test ranged from 50 kph to maximum velocity, making the car roll over.

Reverse quick J-turn:

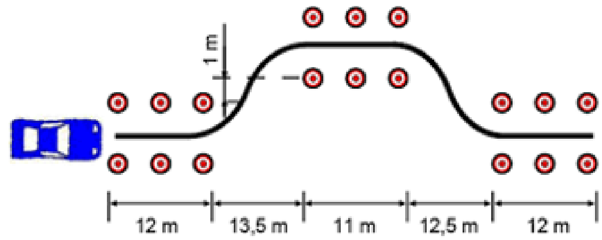

Figure 7: ISO 3888 double lane change.

This test is achieved by transferring the momentum of the car by reversing quickly in a straight line and then turning the wheel sharply while using a brake to lock the front wheels. The driver changes into a forward gear as the nose comes about. Figure 7 shows the x-y bird's eye view data used for the reverse quick J-turn test. And a virtual test run was created based on this data.

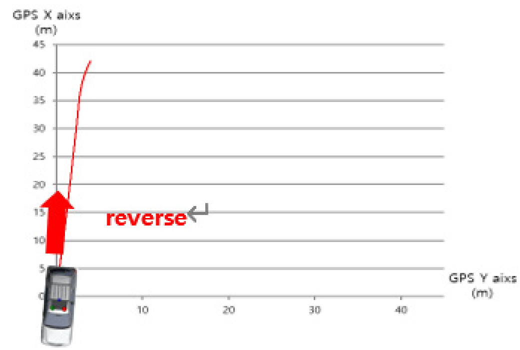

Figure 8: Reverse quick J-turn.

Sine with dwell:

The test has a steering input defined in terms of angle against time. It is a steering plus counter-steering maneuver that a panicked driver might apply to avoid an obstacle on the road. In this test, the possibility of unreasonable steer effort or steer lock was checked, and the performance of suspension and tires was also of interest other than steering performance. Typically vehicle speed is set to 80 kph, and steer input defined in Figure 9 should be implemented. The exact test condition is described in Table 1

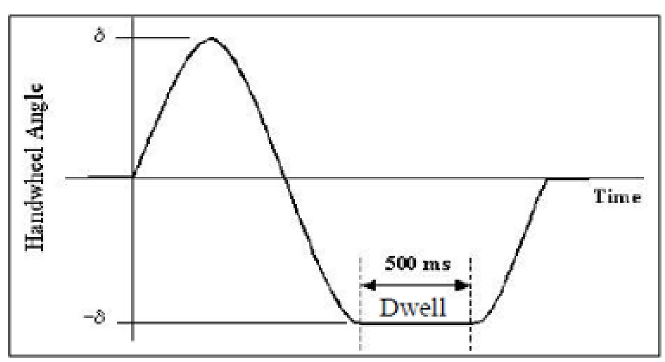

Figure 9: Sine with dwell test.

Table 1: Test mode for risky dynamic maneuvers.

Test mode	Vehicle Speed	Steer rate
reverse J turn	backward 40kph	Quick
double Lane Change	100kph	720deg/s
sine with dwell	80kph	1180deg/s

Results and Discussion

Dynamic test results and discussion

Double Lane Change:

Closed loop tests were implemented by using optimized driver models. Trials were proceeded by measuring the necessary item-related motion and feeling of the steering. Vehicle speed was increased from 50 to 100 kph (Figure 10), and whether steering effort crossed the upper threshold value of 3.07 Nm was checked during the test.

Figure 10: Simulation test for DLC.

Steering wheel angle and torque values were measured in the HILS test and simulation test, which are displayed in Figure 11. No abnormality was found until 70 kph, but the car rolled over at 80 kph, and the maximum steer torque was observed to be over 6.54 Nm which is well over the threshold value. The driver could have lost the wheel's grip and couldn't escape the rollover

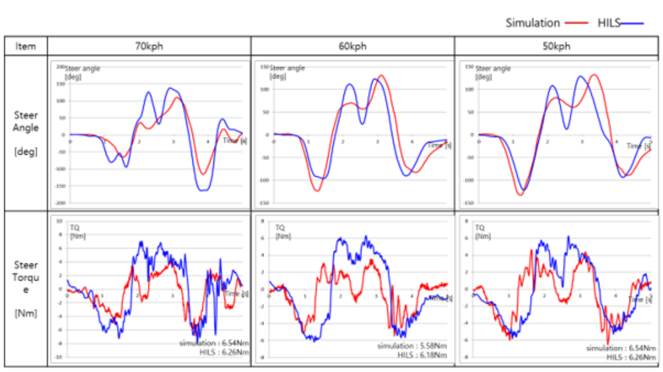

Figure 11: Dynamic maneuver test for DLC (steer angle and torque).

Reverse quick J-turn:

Putting the car in reverse, speeding up, and using a sharp steering maneuver were implemented at reasonable vehicle speed. This test doesn't require a driver model because this is an open-loop test. The test scene was captured in Figures 12-14. Forward quick J-turn is also one of the most dangerous maneuvers to implement on the road. But reverse quick J-turn is a more severe maneuver and demands lots of steering effort because this kind of turning makes a more sudden change in direction and generates a more lateral acceleration. The big difference between the simulation test and the HILS rig test derived from the fact HILS actuator was delayed slightly more than the simulation, and that caused the fluctuation in the data of the latter part.

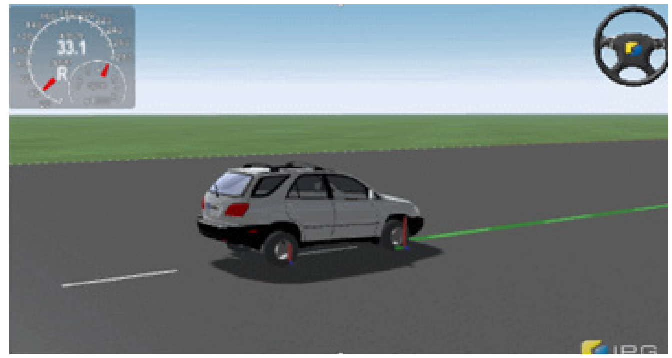

Figure 12: Simulation test for reverse J-turn.

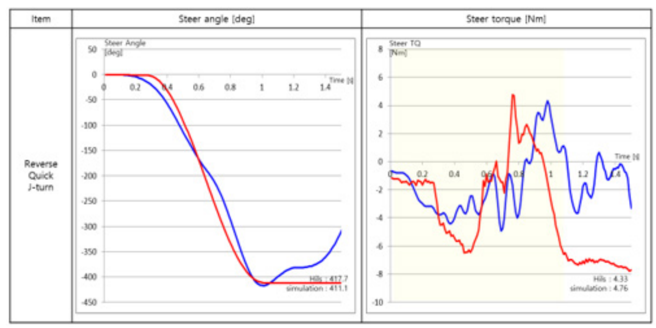

Figure 13: Test for reverse J-turn (steer angle and torque).

Sine with dwell:

This is also an open-loop test with a vehicle speed of 50-80 kph. The test result is shown in Figure 14.

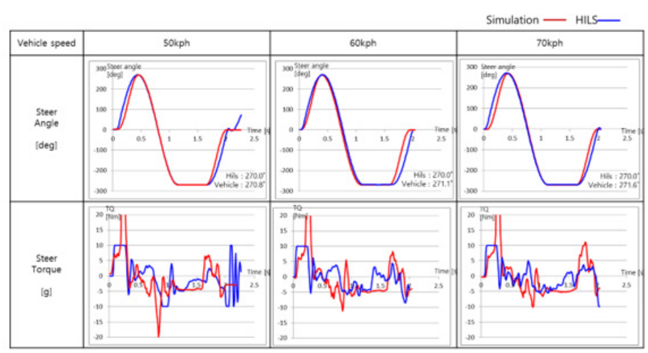

Figure 14: Test for sine with dwell (steer angle and torque).

HILS steering effort couldn't measure the maximum because of the limit of torque sensor at this high steering speed of 1500 deg/s, and test at the rate of 80 kph couldn't be completed because of instability of the vehicle, and the HILS showed the same phenomenon.

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Conclusion

Nowadays, the steering system helps the driver control the vehicle with a motor-driven intelligent assist function called an advanced driver assistance system. UN/ECE R 799 requires the steering control effort necessary to override the directional control provided by the system shall not exceed 50 N, which means 10Nm below (if the lever ratio of the wheel is 0.2m) if we compare the steering rollover control effort threshold value proposed here with that of UN/ECE R 79. This study shows that the steering wheel grip loss effort is far below the regulation. The actual bench test result specifies that the average threshold value of steering effort to lose the wheel's grip is 3.07 Nm. And the dynamic simulation tests conducted using vehicle dynamics software and HILS also shows rollover could happen below 10Nm of steering control effort. So steering control effort requirements should be changed to reduce the rollover fatality.

Even though the actual value from the real vehicle test could not correlate with the result of this study, the well-built and correlated vehicle model, which was used by the university's other project and HILS test, showed a plausible outcome. Using this simulation test on the bench, risky real vehicle tests could be covered and could have protected the real test driver from the potential fatality of the test. And most of all, the rig test could cover the lack of objectiveness of the vehicle test and give it a more repeatable and reproducible test.

Max steer effort per each test case:

Max steer efforts per each test case exceeded the threshold value (refer to Table 2) and need to be regulated for driver's safety in the future. Vehicle makers need to make the steering system easier to handle in this dynamic test and risky situation.

Table 2: Test modes and their test result.

No.	Test mode	Rollover R	Max Steer Effort (Nm)
1	Reverse Quick J_TURN	0.81	4.76
2	Double Lane Change	0.62	6.54
3	Rollover (Sine with dwell)	0.59	Over 20

The developed and utilized validation methods in this study were supported by Halla university's test lab and greatly appreciated for their help. The indicators such as rollover index and steering effort values are good metrics to investigate the impact of the stability and controllability of the SUV vehicle.

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Author

Yoonsu Lee is a Senior at George Washington University Online High School in Ashburn, VA. He loves researching mechanical engineering, AI, computer science, and cybersecurity.