

NHTSA'S LIGHT VEHICLE HANDLING AND ESC EFFECTIVENESS RESEARCH PROGRAM

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ABSTRACT

In 2004, the National Highway Traffic Safety Administration (NHTSA) created its Light Vehicle Handling and electronic stability control (ESC) research program. When first conceived, this program emphasized the development of test maneuvers and analysis methods capable of objectively quantifying handling. At the time, it was envisioned the publication of such results would complement the Agency's NCAP dynamic rollover resistance ratings, thereby allowing consumers to better understand the potential tradeoffs between dynamic rollover stability and good handling.

However, as the 2004 testing proceeded, the Agency's vision of quantifying handling was replaced by the desire to research the safety benefits of ESC. One of the primary objectives of this refocused effort was to develop a way to objectively assess ESC effectiveness on the test track.

The research discussed in this paper examined the ESC effectiveness of five vehicles using twelve maneuvers. Maneuvers are described and their ability to satisfy three ESC effectiveness criteria is discussed. Maneuvers utilized automated and driver-based steering inputs. If driver-based steering was required, multiple drivers were used to assess input variability. To quantify the effects of ESC on handling test outcome, each vehicle was evaluated with ESC enabled and disabled.

INTRODUCTION

The intent of this paper is to describe the tests NHTSA used to explore light vehicle handling and assess ESC effectiveness. All tests were performed at the Transportation Research Center, Inc. (TRC), located in East Liberty, Ohio. Specifically, the facility's Vehicle Dynamics Area (VDA), a 50-acre asphalt test pad, was used. Although dry and wet surfaces were utilized, the wet surfaces introduced an undesirable combination of test variability and sensor

malfunctions. For this reason, this paper only discusses NHTSA's dry testing efforts.

The tests described in this paper occurred during the period of April 4 through October 25, 2004. During this time, the VDA's peak coefficient of friction ranged from 0.91 to 0.97. The slide coefficient varied slightly less, ranging from 0.83 to 0.87. The lowest ambient testing temperature was 38°F, recorded prior to a series of tests performed on October 5, 2004. The highest ambient testing temperature was 85°F, recorded prior to tests performed on June 8, 2004 and August 3, 2004.

Five vehicles equipped with ESC were used. Although they had been used in previous test programs, each vehicle was originally purchased as new by NHTSA, and the respective suspensions were in excellent mechanical condition. Some basic descriptions of these vehicles are presented in Table 1. The measurements provided in this table were taken with a Hybrid II anthropomorphic test dummy positioned in the driver's seat and a full tank of fuel, but without instrumentation or outriggers.

Table 1.
Baseline Vehicle Descriptions.

Vehicle	Description	ESC	Wheelbase (inches)	Weight (lbs)
2003 Toyota Camry	Medium-Sized Car	VSC	107.0	3634
2002 Chevrolet Corvette	Sports Car	Active Handling	104.3	3361
2004 Volvo XC90 4x4	SUV	DTSC	112.3	4803
2003 Toyota 4Runner 4x4	SUV	VSC	109.9	4408
2004 GMC Savana 3500	15-Passenger Van	Stabilitrak	155.5	6770

Tires were of original equipment specification, and were inflated to the pressures recommended by the manufacturer on the respective placards. With the

exception of the NHTSA Fishhook and J-Turn, the tire wear observed during the conduct of maneuvers discussed in this paper was generally not severe, therefore multiple maneuvers were performed with a single tire set.

All tests were performed with the vehicles in NHTSA's Nominal Load condition (driver, instrumentation, full fuel). With the exception of the Chevrolet Corvette, titanium outriggers were installed in lieu of the front and rear bumpers. Given the diversity of the vehicle pool, the authors believe results of this study should be reasonably representative of most light vehicles evaluated in the Nominal Load condition.

TEST MANEUVER GROUPS

Tests were divided into three groups: Test Groups 1, 2, and 3. A programmable steering machine was used to command the Test Group 1 and 3 handwheel inputs, while experienced drivers were used for Test Group 2. Table 2 presents the overall matrix. For the sake of brevity, Test Group 1 maneuver descriptions are not included in this paper. They are described in [1,2,3].

Table 2.
NHTSA's 2004 Light Vehicle Handling / ESC Test Matrix.

Test Group 1	Test Group 2	Test Group 3
<ul style="list-style-type: none"> • Slowly Increasing Steer • NHTSA J-Turn • NHTSA Fishhook 	<ul style="list-style-type: none"> • Modified ISO 3888-2 • Constant Radius Turn 	<ul style="list-style-type: none"> • Closing Radius Turn • Pulse Steer (500 deg/s, 700 deg/s) • Sine Steer (0.5 Hz, 0.6 Hz, 0.7 Hz, 0.8 Hz) • Increasing Amplitude Sine Steer (0.5 Hz, 0.6 Hz, 0.7 Hz) • Sine with Dwell (0.5 Hz, 0.7 Hz) • Yaw Acceleration Steering Reversal (500 deg/s, 720 deg/s) • Increasing Amplitude Yaw Acceleration Steering Reversal (500 deg/s, 720 deg/s)

Test Group 1

Test Group 1 was comprised of maneuvers well known to NHTSA: the Slowly Increasing Steer

(SIS), NHTSA J-Turn and NHTSA Fishhook. In recent years, these maneuvers have been used by NHTSA to evaluate on-road, untripped dynamic rollover resistance. They were included in this study, research designed to evaluate handling and ESC effectiveness, for a number of reasons. First, the maneuvers may offer more utility than previously realized. Tests used to measure dynamic rollover propensity may also reveal important information about important handling characteristics. Second, the instrumentation used for handling research differed slightly from that used for the rollover research program. Measurement of lateral velocity (to facilitate calculation of body slip angles) and vehicle position (via GPS) was not previously performed. Third, it is important to establish a relationship between on-road, untripped rollover, handling, and ESC effectiveness. Understanding what potential compromises may exist between these factors is of great interest to NHTSA (e.g., has the handling of a particular vehicle been degraded so as to improve dynamic rollover resistance?). Finally, these maneuvers will help NHTSA further understand how ESC can affect dynamic rollover resistance.

Test Group 2

Test Group 2 was comprised of two maneuvers: (1) the Constant Radius Turn, and (2) double lane changes performed with a modified version of the ISO 3888 Part 2 test course. Due to the path-following nature of these maneuvers, use of VRTC's programmable steering machine was not feasible. Although maneuvers that rely on the inputs of human drivers are inherently influenced by input variability, NHTSA believed some important insight into vehicle handling could be gained by understanding the subjective impressions of its test drivers. With this knowledge, it was envisioned that a meaningful objective handling test could ultimately be developed. To reduce input variability to the greatest extent possible, up to four experienced drivers were used for each of the Test Group 2 maneuvers.

Constant Radius Turn

The Constant Radius Turn maneuver required the driver attempt to maintain vehicle position on a 200-ft radius circle delineated by pavement marking paint. To begin the maneuver, the driver positioned the vehicle on the circle, with an initial heading tangent to the circle. Beginning from rest, the driver slowly increased vehicle speed and steering such that as it accelerated, the center of the vehicle remained as close to the pavement markings as possible. The driver continued the gradual increase in vehicle speed

until the vehicle could no longer maintain its position on the pavement markings, regardless of the steering wheel angle used, at which point the test was terminated. A total of twelve tests per driver were used. With enabled ESC, the driver performed three left-steer tests followed by three right-steer tests. The ESC was then disabled and the process repeated. Two experienced drivers performed the Constant Radius Turn tests with each of the five test vehicles.

Modified ISO 3888 Part 2 Double Lane Change

Double lane change maneuvers can provide valuable information about the handling of a vehicle in a highly transient situation. Unlike maneuvers such as the NHTSA Fishhook, lane changes are path-following in nature, and therefore possess an inherently high face validity. These are avoidance maneuvers that frequently occur in the real world.

There are many different double lane changes used in industry. These include ISO 3888 Parts 1 and 2, the Consumer’s Union short and long courses, and that presented to NHTSA by the Alliance of Automobile Manufacturers.

NHTSA used the ISO 3888-2 lane change to evaluate untripped, dynamic rollover resistance in Phase IV of its Rollover Research Program. The course was comprised of three lanes, two of which had their width defined by the width of the vehicle being evaluated (a consideration that endeavors to impose similar severity for all vehicles, and to reduce steering input variability). After performing these tests in Phase IV, the authors concluded that use of the maneuver for quantifying rollover resistance was not appropriate, and that it may be better suited for near-limit subjective handling assessment. The reasons for this were two-fold: (1) due to its length, the second lane of the course briefly allowed the

vehicles to stabilize before being steered toward the third lane, and (2) the width of the second lane was so narrow that the vehicles were unable to generate significant rear slip angles without striking cones (thus violating a validity requirement).

To maintain some of the desirable features of the ISO 3888-2 course (e.g., adjusting dimensions to the vehicle being evaluated), but with increased maneuver severity, the second lane was replaced with a gate comprised of only two pylons. The width of this gate still remained a function of the vehicle being evaluated, and its longitudinal position remained constant regardless of what test vehicle was being used. Figure 1 presents the modified ISO 3888-2 course layout, while Table 3 specifies what lane/gate widths were used for each vehicle. Due to the track width similarities of the Volvo XC90, Savana 3500, and Chevrolet Corvette, the course layout used for these vehicles was held constant.

Table 3.
Modified ISO 3888-2 Entrance Lane and Obstacle Gate Widths.

Vehicle	Vehicle Width (m)	Entrance Lane Width “A” (m)	Obstacle Gate Width “B” (m)
2004 GMC Savana 3500	1.98	2.43	2.98
2004 Volvo XC90 4x4	1.88	2.30	2.86
2003 Toyota 4Runner 4x4	1.85	2.30	2.86
2002 Chevrolet Corvette	1.82	2.30	2.86
2003 Toyota Camry	1.75	2.17	2.74

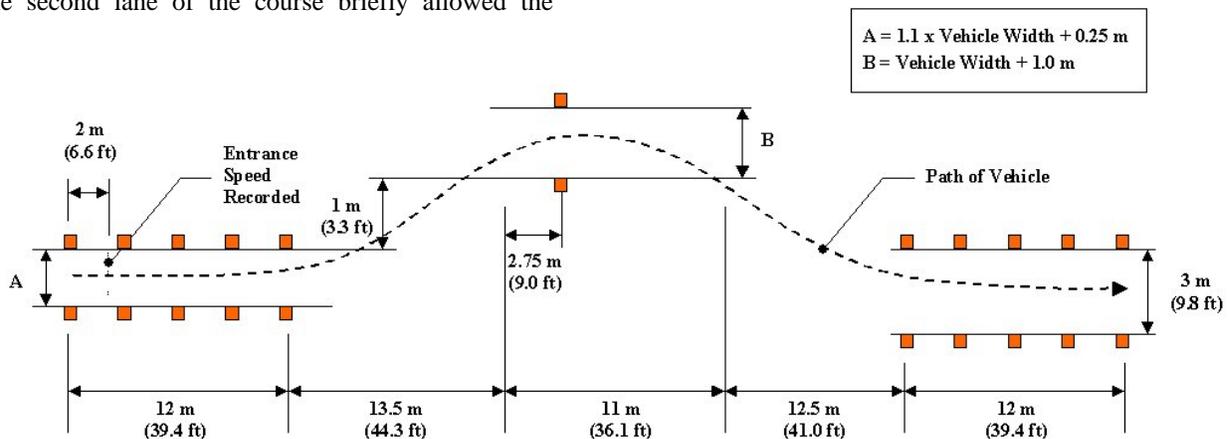


Figure 1. Modified ISO 3888-2 course layout.

Four experienced drivers performed the Modified ISO 3888-2 tests, with each of the five test vehicles. All vehicles were evaluated with their respective ESC systems enabled and disabled. Each driver performed the disabled ESC tests prior to those performed with the systems enabled.

To begin this maneuver, the vehicle was driven in a straight line at the desired entrance speed. Prior to entering the first lane, the driver released the throttle and, at a nominal distance of 6.6 ft (2.0 m) after entering the first lane, the maneuver entrance speed was recorded (as shown in Figure 1). No throttle input or brake application was permitted during the remainder of the maneuver. The driver steered the vehicle from the entrance lane, through the offset (left) gate, then through the exit lane.

Drivers iteratively increased maneuver entrance speed from approximately 35 mph. The iterations continued until “clean” tests could no longer be performed (the desired course could not be followed without striking or bypassing cones), however each driver was instructed to perform only ten tests per vehicle configuration. Each driver was required to perform at least two “clean” runs using their maximum maneuver entrance speed. Runs that were not “clean” were not considered to be valid, and were not used for later analysis. To reduce any confounding effect tire wear may have on the modified ISO 3888-2 double lane change results, a new tire set was installed on each vehicle after two drivers had completed their respective lane changes (i.e., two drivers shared one tire set).

Test Group 3

Test Group 3 included maneuvers developed by the Alliance of Automobile Manufacturers (subsequently referred to as the Alliance for brevity) and NHTSA. The Alliance-developed maneuvers were originally conceived to provide data to be used to *objectively* quantify light vehicle handling. For this reason, these maneuvers were each performed with a programmable steering machine.

NHTSA’s Test Group 3 maneuvers were developed after the Alliance had developed its handling maneuvers. Conceptually, these maneuvers were nearly identical to those developed by the Alliance, however they included a provision that allowed the maneuvers to be adapted to the vehicle being evaluated. Although the Test Group 3 maneuvers utilized a programmable steering machine for all steering inputs, the rates and magnitudes are believed to be within the capabilities of a human driver.

With the exception of the Closing Radius Turn maneuver, handwheel angles used for the Test Group 3 tests were nominally increased in 20-degree increments from 60- to 300-degrees to increase maneuver severity. However, a test series was terminated once excessive yaw caused the vehicle’s final heading to be approximately 90-degrees from the initial direction of travel.

Closing Radius Turn

Conceptually, this maneuver simulates a situation where a driver enters a tight, closing radius corner with excessive speed (e.g., a low-speed exit ramp from a highway or interstate roadway). In this scenario, the driver begins to slowly steer the vehicle onto the exit ramp, but is then surprised by the rate at which the curve tightens. As an instinctual countermeasure, the driver rapidly inputs more and more steering as they travel deeper into the turn. If excessive speed is present, the vehicle may not respond to the additional steering commands input by the driver. This can lead to a roadway departure in which the front of the vehicle departs the roadway before the rear.

To begin the maneuver, the driver accelerated the vehicle to a speed of approximately 52 mph, at which point the throttle was released and the steering controller engaged. Once the vehicle had coasted down to a speed of 50 mph, the steering machine automatically executed one of the steering inputs shown in Figure 2.

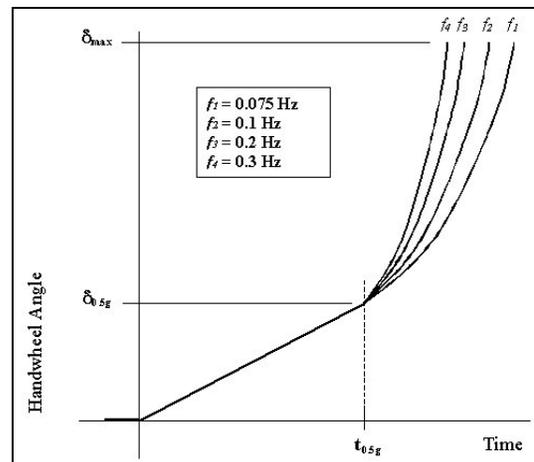


Figure 2. Closing Radius Turn handwheel inputs.

As shown in Figure 2, the Closing Radius Turn maneuver was comprised of two parts. The first was a linear increase in steering angle from zero to the

average handwheel angle capable of achieving 0.5g (corrected for roll effects) during the six previously described SIS tests. The second part of each maneuver was comprised of a partial sinusoid, based on one of four frequencies: 0.075, 0.1, 0.2, or 0.3 Hz. For each frequency, one of three peak steering angle magnitudes was used: $1.5 \cdot \delta_{90\% \text{MaxAY}}$, $2.0 \cdot \delta_{90\% \text{MaxAY}}$, or 360 degrees, where $\delta_{90\% \text{MaxAY}}$ was the handwheel angle measured at 90 percent of the average maximum lateral acceleration achieved during each vehicle's respective SIS tests.

Pulse Steer

The Pulse Steer maneuver was comprised of triangular steering inputs performed with constant handwheel rates and incrementally increasing handwheel angles. Two steering ramp rates were used, 500 deg/sec or 700 deg/sec, and each maneuver only used one rate per test (i.e., the first and second ramp rates were always the same). Figure 3 describes the Pulse Steer steering inputs.

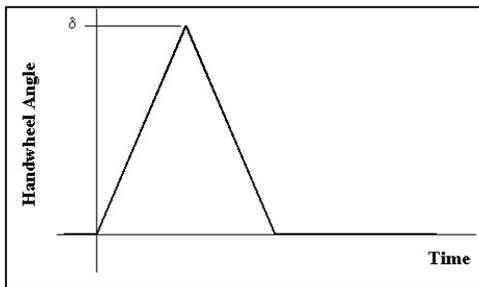


Figure 3. Pulse Steer handwheel inputs.

Sine Steer

The four Sine Steer maneuvers performed in this study were each comprised of one single cycle sinusoidal steering input. The peak magnitudes of the first and second half-cycles were identical. Frequencies of 0.5, 0.6, 0.7 and 0.8 Hz were used. Figure 4 provides an example of the Sine Steer steering inputs.

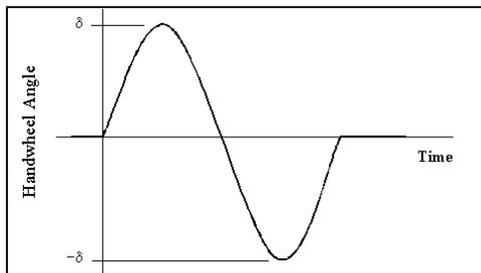


Figure 4. Sine Steer handwheel inputs.

Sine with Dwell

In a manner nearly identical to the Sine Steer tests, the two Sine with Dwell maneuvers were based on one single cycle sinusoidal steering input. Although the peak magnitudes of the first and second half-cycles were identical, the Sine with Dwell maneuver included a 500 ms pause after completion of the third quarter-cycle of the sinusoid. Frequencies of 0.5 and 0.7 Hz were used. Figure 5 provides an example of the Sine with Dwell steering inputs.

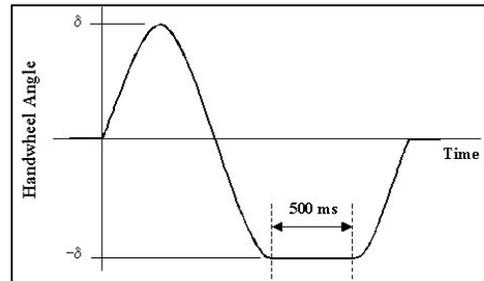


Figure 5. Sine with Dwell handwheel inputs.

Increasing Amplitude Sine

Like the other maneuvers based on sinusoidal steering, the three Increasing Amplitude Sine maneuvers were based on one single cycle sinusoidal steering input. However, the amplitude of the second half-cycle was 1.3 times greater than the first half-cycle for this maneuver. Frequencies of 0.5, 0.6, and 0.7 Hz were used for the first half cycle; the duration of the second half cycle was 1.3 times that of the first. Figure 6 provides an example of the Increasing Amplitude Sine steering inputs.

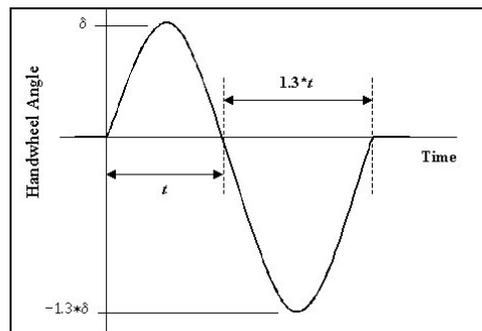


Figure 6. Increasing amplitude sine handwheel inputs.

Yaw Acceleration Steering Reversal (YASR)

The Yaw Acceleration Steering Reversal (YASR) maneuver was designed to trigger changes in

direction of steer at maximum yaw rate. In theory, this timing should maximize maneuver severity by allowing each vehicle to seek out its own yaw natural frequency. The maneuver was comprised of three steering ramps: an initial steer, a steering reversal, and a return back to zero. The rate of each ramp was constant for a given maneuver at either 500 or 720 deg/sec (i.e., different ramp rates were not used during the same maneuver). Figure 7 provides an example of the YASR handwheel inputs.

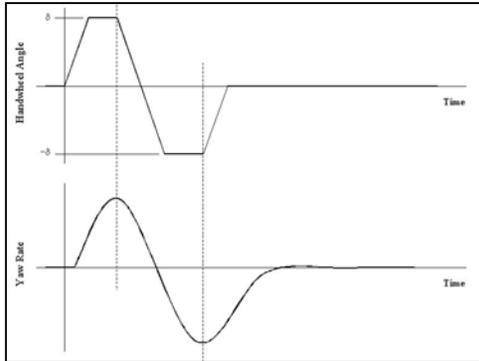


Figure 7. Yaw Acceleration Steering Reversal handwheel input description.

Increasing Amplitude Yaw Acceleration Steering Reversal (IAYASR)

Figure 8 provides an example of the IAYASR handwheel inputs. Like the previously described maneuver, the Increasing Amplitude Yaw Acceleration Steering Reversal (IAYASR) maneuver was designed to trigger changes in direction of steer at maximum yaw rate, and was comprised of three steering ramps: an initial steer, a steering reversal, and a return back to zero. The rate of each ramp was constant for a given maneuver at either 500 or 720 deg/sec. The key difference between this maneuver and the YASR maneuver was the magnitude of the initial steer, as it was 1.3 times less than the peak reversal magnitude. Conceptually, this maneuver was very similar to the Increasing Amplitude Sine Steer, but rather than relying on handwheel inputs being based on a finite set of frequencies, the vehicle was able to seek out its own yaw natural frequency.

MANEUVER DISCUSSION

In the previous section, the authors described the maneuvers used by NHTSA’s 2004 Light Vehicle Handling and ESC Effectiveness Program. This section discusses what elements NHTSA believes are important when considering ESC effectiveness and provides an overall maneuver assessment summary.

Throughout the remainder of this paper, the terms “excessive yaw” and “spinout” are frequently used when discussing yaw motion. In the context of this paper, the authors define excessive yaw as a situation where the final heading of the vehicle being evaluated is 90-degrees or more from the initial path (before the maneuver’s handwheel inputs are initiated). NHTSA’s proposed definition of spinout is provided later in this paper.

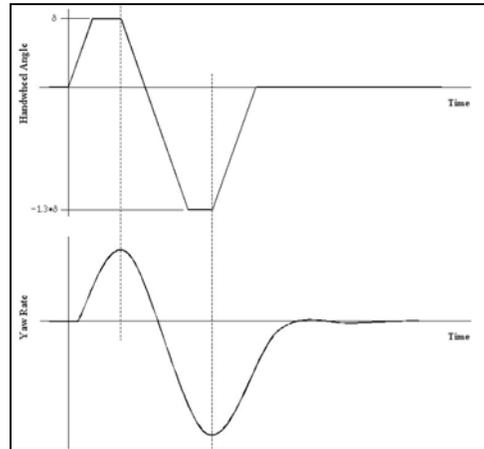


Figure 8. Increasing amplitude yaw acceleration steering reversal handwheel input description.

Elements of a “Good” ESC Detection Maneuver

NHTSA researchers believe a maneuver capable of providing a good assessment of ESC effectiveness should possess the following attributes:

1. The ability to impose a high level of severity on the vehicle and its respective ESC
2. Is repeatable and reproducible
3. Considers lateral stability and responsiveness

Element #1: Ability to impose a high level of severity

The authors consider each of the twelve maneuvers used in this study to be “limit” maneuvers. In each case, steering and/or vehicle speed was increased in a manner that ultimately brought each vehicle up to the limit of lateral adhesion. When it was enabled, ESC intervention was detected during the conduct of all twelve maneuvers.

Test Group 1

For use in this study, the maximum handwheel angle used during the SIS tests was 270-degrees. This

handwheel angle magnitude, when combined with a 50-mph target speed, allowed experimenters to measure maximum lateral acceleration and quasi-steady state lateral stability. In some cases, SIS tests have induced excessive yaw and even two-wheel lift [4]. As such, NHTSA considers the SIS maneuver to be a severe test, provided a maximum handwheel angle of 270-degrees is used.

The NHTSA J-Turn and Fishhook maneuvers were designed to provide experimenters with ways of objectively quantifying on-road, untripped rollover propensity. Although the handwheel angles used by these maneuvers are within the capabilities of a human driver, the combination of sudden inputs and optimized steering reversals (in the case of the NHTSA Fishhook) make the NHTSA J-Turn and Fishhook maneuvers two of the most severe tests known to NHTSA.

Test Group 2

The maneuver severity imposed by the Constant Radius Turn maneuver was approximately equal to that of the previously described Slowly Increasing Steer maneuver. Since the maneuver can be used to measure maximum lateral acceleration, NHTSA considers the Constant Radius Turn maneuver to be a severe test. However, unlike the SIS maneuver, the Constant Radius Turn maneuver requires the driver provide throttle and steering inputs. For this reason it is very important to have an experienced test driver perform this maneuver. Abrupt applications of throttle and/or steering may unsettle the vehicle as it approaches its limit of lateral adhesion, and may not provide an accurate portrayal of the vehicle's actual limit state (e.g., whether the vehicle is terminal under- or oversteer).

The modified ISO 3888-2 lane change maneuver severity often varied as a function of driver steering strategy. Even two tests performed by the same driver, with nearly identical maneuver entrance speeds, contained steering input variability (i.e., different timing, magnitudes, and rates), and this variability was capable of influencing the magnitude of the vehicle's yaw responses. Driving style also influenced the extent to which ESC intervened. ESC intervention observed during the modified ISO lane changes differed from test to test and driver to driver, and intervention intervals varied from quick brake pulses to extended periods of substantial modulation at one or more of the wheels.

In summary, while the maneuver did provide an opportunity for experimenters to observe some limit

behavior, the maneuver was unable to consistently produce responses as severe as those capable of being produced with the automated steering controller.

Test Group 3

With only one exception, the Test Group 3 maneuvers performed in this study were able to induce excessive yaw, for each vehicle, when the respective ESC systems were disabled (when 0.7 Hz and 0.8 Hz Sine Steer tests were performed with the GMC Savana, even handwheel angle inputs of 300-degrees were unable to produce excessive yaw). This makes these maneuvers well suited for assessing oversteer mitigation, one of the most important attributes of ESC.

Table 4 presents a list of Test Group 3 maneuvers, and the commanded handwheel angle used during the test for which excessive yaw was observed. Maneuvers requiring the least amount of steering are believed to be more severe than those requiring large handwheel angles.

Pulse Steer. In terms of eliciting excessive yaw in the disabled ESC configuration, the Pulse Steer maneuver was the least effective maneuver for three of the five vehicles (the Volvo XC90, Toyota Camry, and Chevrolet Corvette). With this maneuver, use of 700 deg/sec handwheel ramp rates required 20 to 60 degrees more steering to produce excessive yaw than did those maneuvers performed at 500 deg/sec.

Since Pulse Steer steering inputs are completed quickly, large magnitudes must be used to excite oversteer. When considering a maneuver to be able to identify whether a vehicle is equipped with an effective ESC, this is a disadvantage since there will likely be vehicles that successfully complete the maneuver (i.e., do not produce excessive yaw) even though they are not equipped with an ESC.

Sine Steer. As suggested by the Alliance, the Sine Steer maneuver was performed using four frequencies. Although time-consuming, the Alliance's recommendation to include four frequencies is understandable. Since all vehicles do not possess the same yaw natural frequency, it is unlikely that the use of a sinusoidal steer maneuver based one frequency will be equally effective across all light vehicles. The more frequencies considered, the greater the likelihood the correct one will be selected. In the context of the work described in this paper, the "correct" frequency is that which induces the greatest yaw response with the smallest amount of steering.

Table 4.
Handwheel Input Magnitudes Capable of Producing Excessive Yaw (in degrees).

Vehicle	Maneuver														
	Pulse Steer		Sine Steer				Sine with Dwell		Increasing Amplitude Sine Steer			YASR		IAYASR	
	500 deg/s	700 deg/s	0.5 Hz	0.6 Hz	0.7 Hz	0.8 Hz	0.5 Hz	0.7 Hz	0.5 Hz	0.6 Hz	0.7 Hz	500 deg/s	720 deg/s	500 deg/s	720 deg/s
2004 Volvo XC90 4x4	200	240	140	150	170	180 ¹	130	130	160	160	160	140	140	160	160
2004 GMC Savana 3500	240 ²	280	240	300	N/A	N/A	170	190	220	240	290	200	240	220	220
2003 Toyota Camry	240	260	170	210	230	270	160	160	210	200	200	180	200	180 ²	200
2003 Toyota 4Runner 4x4	200 ²	300	180	180	200	210	180	170	210	210	200	180	180	200	200
2002 Chevrolet Corvette	180	220	120	140	140	160	120	110	140	130	140	140	140	140	160

¹Test series was terminated prematurely. The last test only allowed the vehicle's final heading to be 80 degrees from the initial path.

²Test series was terminated prematurely. The last test only allowed the vehicle's final heading to be 85 degrees from the initial path.

For each vehicle evaluated in this study, use of 0.5 Hz steering most effectively excited an oversteer response. Depending on the vehicle, 0.5 Hz steering was able to produce excessive yaw with 10 to 100 degrees less handwheel angle input than for the other frequencies. Use of 0.5 Hz sinusoidal steering was particularly effective for producing excessive yaw with the Chevrolet Corvette (120 degrees), Volvo XC90 (140 degrees), and Toyota Camry (170 degrees). In the case of the GMC Savana, only use of 0.5 and 0.6 Hz steering was able to produce excessive yaw. Figure 9 presents these tests, performed with 240 and 300-degrees of steer, respectively. The 0.7 Hz and 0.8 Hz Sine Steer tests were unable to produce excessive yaw, even with handwheel angles as large as 300-degrees.

Sine with Dwell. In a manner nearly identical to those used in the Sine Steer maneuver, the Sine with Dwell maneuver uses left-right sinusoidal handwheel inputs. The only difference between these maneuvers is a 500 ms pause that occurs immediately after the peak right-steer handwheel reversal magnitude had been achieved. In this respect, the handwheel inputs used for the Sine with Dwell maneuver are much like those used in the NHTSA Fishhook, although the pause duration is six times shorter and the handwheel magnitudes tend to be less extreme.

Generally speaking, the Sine with Dwell was the maneuver best able to excite an oversteer response from the vehicles examined. The only exception was for the Toyota Camry, however the difference in the steering angle required to produce excessive yaw during Sine with Dwell testing (180 degrees) was negligible when compared to that required by the 0.5 Hz Sine Steer maneuver (only 10 degrees less).

Increasing Amplitude Sine Steer. The Increasing Amplitude Sine Steer is similar to the Sinusoidal Steer maneuver, with the exception being the second half cycle is comprised of an amplitude and duration 1.3 times greater than the first half cycle. With the exception of the GMC Savana, the steering angles capable of producing excessive yaw during the Increasing Amplitude Sine Steer maneuver were within the range of handwheel angles established with the Sine Steer maneuver.

The Increasing Amplitude Sine Steer maneuver produced inconsistent results for the different vehicles. In the case of the GMC Savana, as the steering frequency was increased from 0.5 to 0.7 Hz, the handwheel angle necessary to produce excessive yaw increased from 220 degrees at 0.5 Hz to 300 degrees at 0.7 Hz. Conversely, the Toyota Camry required less steering magnitude as the frequency of the inputs was increased, although this phenomenon

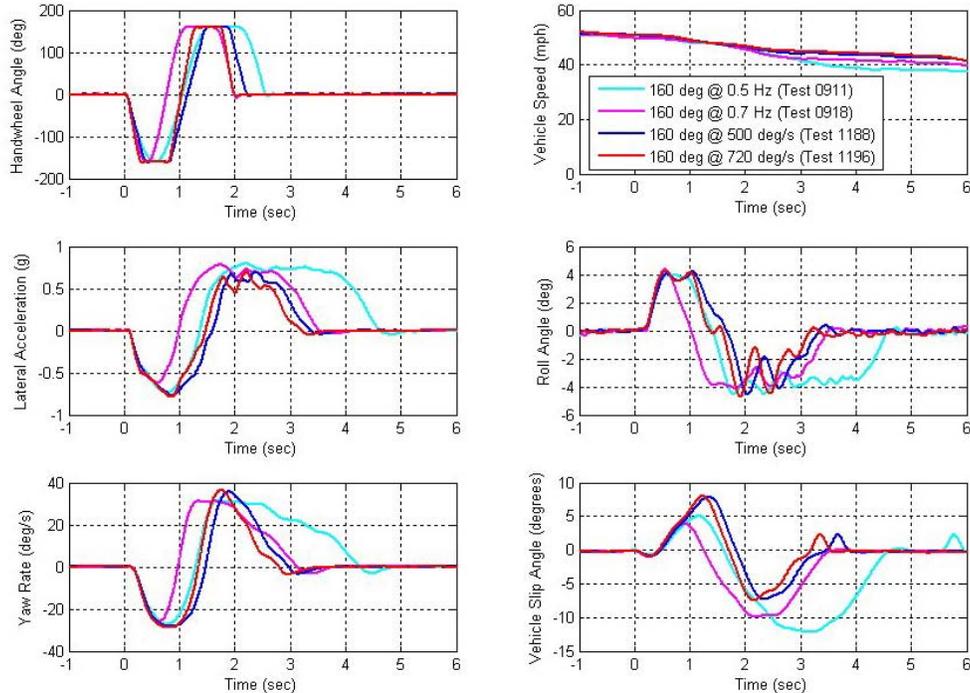


Figure 9. Handwheel inputs and vehicle responses produced during Sine Steer tests performed with a 2004 GMC Savana 3500.

was less extreme than that seen during GMC Savana testing. At 0.5 Hz, the Toyota Camry required 220 degrees of steer to produce excessive yaw, while 0.7 Hz required 190 degrees. Different still, the Toyota 4Runner, Volvo XC90, and Chevrolet Corvette appeared to be insensitive to increases in handwheel input frequency. The handwheel angles capable of producing excessive yaw with these vehicles were, respectively, within 10 degrees regardless of the commanded frequency.

Yaw Acceleration Steering Reversal. The YASR maneuver was designed to trigger changes in direction of steer at maximum yaw rate. In theory, this timing should maximize maneuver severity by allowing each vehicle to seek out its own yaw natural frequency. The maneuver was comprised of three steering ramps: an initial steer, a steering reversal, and a return back to zero. The rate of each ramp was constant for a given maneuver at either 500 or 720 deg/sec (i.e., different ramp rates were not used during the same maneuver).

Realizing that this maneuver is still in an early stage of development, results appear to be encouraging. For all five vehicles, the steering required to produce excessive yaw with 720 deg/sec handwheel rates was within the respective range observed during Sine Steer tests performed at 0.5 to 0.6 Hz. In the case of the GMC Savana, the YASR performed with 500

deg/sec handwheel ramps produced excessive yaw with up to 40-degrees less amplitude than those required by 0.5 to 0.6 Hz sinusoidal steering. No YASR required less steering than that required by the Sine with Dwell maneuver to produce excessive yaw. That said, tests performed with the Toyota Camry using 500 deg/sec steering ramps were able to achieve excessive yaw using steering magnitudes equivalent to those required by the 0.5 and 0.7 Hz Sine with Dwell tests performed with this vehicle.

Increasing Amplitude Yaw Acceleration Steering Reversal. Conceptually, this maneuver is very similar to the Increasing Amplitude Sine Steer, but rather than relying on handwheel inputs being based on a finite set of frequencies, the vehicle was free to seek out its own yaw natural frequency. Like the YASR, the IAYASR maneuver was designed to trigger changes in direction of steer at maximum yaw rate, and is comprised of three steering ramps: an initial steer, a steering reversal, and a return back to zero. The rate of each ramp was constant for a given maneuver at either 500 or 720 deg/sec. The key difference between the IAYASR and the YASR was the magnitude of the initial steer, as it was 1.3 times less than the right steer peak magnitude.

Many of the handwheel angles capable of producing excessive yaw during YASR tests were also able to do so during comparable IAYASR tests (Toyota

Camry at 500 and 720 deg/sec, and Chevrolet Corvette at 500 deg/sec).

During the IAYASR maneuver, the only vehicle and steering rate combination to induce excessive yaw at a lower handwheel angle than those used in the YASR was the GMC Savana with at steering rate of 720 deg/sec. Using the increasing amplitude steering technique, excessive yaw was produced using 20 degrees less steering than was necessary with symmetric steering (220 vs. 240 degrees).

Element #2: Is repeatable and reproducible

Of the twelve maneuvers examined in this study, the authors believe only those executed with steering machine-based handwheel inputs are appropriate for an objective evaluation of ESC effectiveness. Throughout its Light Vehicle Rollover Research Program, NHTSA has gained extensive experience with the use of programmable steering machines. Use of these machines has made dynamic rollover testing a reality, since the steering inputs are accurate, repeatable, and reproducible. Recent NHTSA technical reports have established the ability for the steering machines used by NHTSA to successfully achieve the desired handwheel rates and magnitudes [1,2,3]. NHTSA is pleased with its automated steering capabilities, and believes the utility of this technology extends beyond the realm of dynamic rollover resistance testing.

Maneuvers performed in Test Groups 1 and 3 were all performed with a steering machine. For this reason, the steering inputs were inherently repeatable and reproducible. Similarly, the output from these tests is also expected to be repeatable and reproducible, provided careful attention to tire wear is used. This has been demonstrated for the NHTSA Fishhook, J-Turn, and Slowly Increasing Steer maneuvers in [1,3,4], and although repeatability analyses were beyond the scope of this study, the authors believe the maneuvers performed in Test Group #3 will retain the repeatability and reproducibility established by previously performed rollover maneuvers.

Each of the maneuvers performed in Test Group 2 relied on test drivers to provide steering and throttle inputs. When compared to results from Test Groups 1 and 3, this resulted in degraded input repeatability and reproducibility. The input variability seen during the lane changes performed in this study were consistent with results previously published by NHTSA in [1].

In summary, since the maneuvers performed in Test Groups 1 and 3 were performed with a steering machine, each maneuver possesses an acceptable level of repeatability and reproducibility. Conversely, the authors do not believe the Modified ISO 3888-2 double lane change or the Constant Radius Turn maneuvers provide sufficiently high repeatability and reproducibility since test drivers are responsible for the necessary steering and throttle inputs.

Element #3: Considers lateral stability and responsiveness

In this paper, lateral stability refers to a vehicle's ability to resist excessive yaw. As will be discussed in this section, there are many maneuvers capable of assessing lateral stability, particularly those contained within Test Group 3. However, when considering ESC effectiveness, lateral stability is not the only important consideration. Achieving good lateral stability should not be achieved at the expense of responsiveness, or the ability of the vehicle to react to the inputs commanded by the driver.

There are a number of ways to consider responsiveness. However, the metric(s) used for one maneuver may not be appropriate for another. In addition to discussing lateral stability, this section explores some issues pertaining to responsiveness.

Test Group 1

Although the NHTSA Fishhook and J-Turn maneuvers both have the ability to provide information relevant to the handling (e.g., lateral stability, the path deviation, time-to-peak response, etc.), it is important to recognize these maneuvers are designed primarily for the evaluation of dynamic rollover propensity. The inputs used for both maneuvers contain periods of time where the handwheel angle is held constant for extended durations, a feature that gives experimenters the ability to examine how vehicles respond to high roll rates followed by extended periods of high lateral acceleration. Furthermore, in the case of the NHTSA Fishhook, the *roll* response of the vehicle directly commands the handwheel reversals input by the steering machine.

If the scope of NHTSA's ESC effectiveness research was limited to determining what effect ESC has on on-road untripped rollover, the authors believe use of the NHTSA Fishhook would be appropriate. However, since the greatest benefit of ESC is oversteer mitigation, and NHTSA's present efforts

seek to develop a criteria to identify whether a vehicle is equipped with an ESC, the authors believe use of maneuvers capable of exciting *yaw* motion are more desirable than those used to excite *roll* motion. The authors believe there is a clear, conceptual difference in these two types of maneuvers. Therefore, when considering lateral stability and responsiveness, the authors believe maneuvers capable of effectively evaluating yaw motion should be emphasized.

The SIS maneuver provides useful data about a vehicle's linear range and limit performance. Since the primary objective of this study was to identify a maneuver (or set of maneuvers) capable of determining whether a vehicle is equipped with an ESC, linear range performance is not of interest—ESC does not intervene while the vehicle is being operated in this range. That said, ESC does typically intervene as the vehicle approaches its limit of lateral adhesion during the later part of the SIS maneuver. The most common intervention is the reduction of drive torque via reduction or removal of the driver's throttle commands. This is generally a very effective way of settling the vehicle, albeit at the expense of the driver's ability to maintain constant vehicle speed.

Although it is a somewhat atypical phenomenon, NHTSA has evaluated vehicles that have exhibited terminal oversteer during SIS tests, even when ESC was enabled [2]. For this reason, there is evidence the maneuver is capable of providing valuable information about the lateral stability at the vehicle's limit of adhesion. The maneuver can also provide valuable information pertaining to responsiveness. For example, items such as: (1) maximum lateral acceleration, (2) the degraded output responses of the vehicle to increasing handwheel magnitudes (e.g., of lateral acceleration, yaw rate, etc.), and (3) the degraded effect of throttle application as the maneuver progressed, are all easily monitored during execution of the SIS.

That said, the authors do not believe the test provides as much insight into lateral stability and responsiveness as other maneuvers evaluated in this study, particularly those discussed in Test Group #3. Furthermore, since the vehicle is being operated in a quasi steady state for a majority of the maneuver's duration, the authors believe that the maneuver is not particularly well suited to consider of responsiveness.

In summary, although the maneuvers performed in Test Group 1 can be accurately and repeatably performed with a steering machine, the authors do

not believe the NHTSA Fishhook, J-Turn, or SIS maneuvers have the ability to provide inputs appropriate for the measurement of lateral stability and responsiveness necessary to determine whether a vehicle is equipped with an ESC.

Test Group 2

To quantify lateral stability and responsiveness during tests performed with the modified ISO 3888-2 double lane change, each driver was required to complete a questionnaire. This questionnaire, most of which was developed by the Alliance, instructed the drivers to describe their subjective impressions of the test vehicles using a rating scale of 1 to 10. The drivers responded to a total of 13 questions, five of which specifically targeted ESC intervention and effectiveness.

The modified ISO 3888-2 double lane change clearly facilitates measurement of lateral stability and responsiveness since the drivers are specifically asked to describe their impressions pertaining to these factors. However, while the responses to these questions are capable of providing useful information about handling and ESC intervention, they are all subjective impressions based on inputs with relatively high steering variability (especially when compared to those produced with a steering machine). Even when results from the questionnaire are normalized against those recorded for a control vehicle, the authors do not believe the responses are capable of measuring lateral stability and responsiveness in the context of establishing a minimum level of ESC effectiveness.

Like the SIS maneuver, the Constant Radius Turn maneuver provides useful data about a vehicle's limit performance, and can typically trigger an ESC intervention as a vehicle approaches its limit of lateral adhesion. The most common form of intervention is the reduction of drive torque via reduction or removal of the driver's throttle commands. As previously mentioned, this is generally a very effective way of settling the vehicle, albeit at the expense of the driver's ability to increase vehicle speed to increase maneuver severity (a concern usually reserved for the test track, not real world driving). The maneuver is not particularly well suited to consider responsiveness, as the vehicle is operated in a quasi steady state for a majority of its duration. That said, since the driver performs all handwheel inputs, measures of the steering required to maintain lane position and throttle modulation effectiveness are both interesting outputs. However, once ESC intervenes it is very likely that throttle

modulation will not have much effect adjusting vehicle speed unless the ESC deems the vehicle to be back under control; and if throttle modulation is not capable of increasing vehicle speed, varying the steering wheel angle will not be necessary.

In summary, the authors do not believe the Constant Radius Turn maneuver or the modified ISO 3888-2 double lane change have the ability to provide inputs appropriate for the measurement of lateral stability and responsiveness necessary to determine whether a vehicle is equipped with an ESC.

Test Group 3

With the exception of the 0.7 and 0.8 Hz Sine Steer tests performed with the GMC Savana, all Test Group 3 maneuvers were able to induce excessive oversteer when ESC was disabled. When ESC was enabled, only one instance of excessive yaw was observed: during a 0.8 Hz Sine Steer test performed with the Toyota Camry. Although some Test Group 3 maneuvers may be able to produce excessive yaw with lesser steering magnitudes than others, the authors believe each maneuver in this group is capable of providing valuable information about lateral stability, with the Sine with Dwell, Increasing Amplitude Sine, and the two Yaw Acceleration Steering Reversals being particularly well suited for the evaluation of ESC oversteer mitigation effectiveness.

There are many, many ways for the data output by the Test Group 3 maneuvers to be used to quantify responsiveness. Fortunately, the scope of NHTSA's current work is narrow: isolate a maneuver and metric(s) capable of assessing ESC effectiveness. After meeting with automakers, ESC manufacturers, and testing organizations, NHTSA ultimately decided the best way to quantify responsiveness, using Test Group 3 maneuvers, was to consider lateral displacement.

In order for displacement to effectively assess responsiveness, the maneuver must provide an opportunity for the vehicle to traverse laterally without relying on excessive yaw to do so. Maneuvers such as the Sine Steer, Sine with Dwell, Increasing Amplitude Sine, and the two Yaw Acceleration Steering Reversals all basically emulate single lane changes. As such, these maneuvers each provide an opportunity to study how increasing handwheel angles and ESC intervention affect lateral displacement. The Pulse Steer, on the other hand, was not based on a reverse steer input. The steering wheel angle was increased from zero to a target

magnitude, then back to zero. For this reason, the ability of the Pulse Steer to displace the vehicle laterally prior to generating excessive yaw is compromised, and the concept of determining a minimum lateral displacement from the initial path makes little sense. Lateral deviation only occurs in one direction, and there is no chance for the vehicle to recover from the initial steering input.

In summary, the authors believe the Sine with Dwell, Increasing Amplitude Sine, and the two Yaw Acceleration Steering Reversals each provide inputs capable of measuring lateral stability and responsiveness in a way that can adequately determine whether a vehicle is equipped with an effective ESC. While the Sine Steer maneuver shares some of the attributes possessed by the other reverse-steer maneuvers, each iteration (i.e., frequency) of the maneuver includes limited frequency content and symmetric steering. This requires multiple frequencies be used in a suite of Sine Steer maneuvers. If only one Sine Steer frequency is used, the results of this study indicate a vehicle's "worst-case" performance may not be realized.

Maneuver Assessment Summary

This study evaluated twelve maneuvers capable of providing insight into ESC effectiveness. The primary objective of this study was to decide which, if any, of these maneuvers could be used by NHTSA to determine whether a vehicle is equipped with an ESC capable of satisfying a series of minimum effectiveness criteria. As explained in the previous sections, three evaluation criteria were used to assess how well each maneuver was able to satisfy this objective. Table 5 provides a summary of the findings. To simplify the summary, each maneuver has been assigned an adjectival rating ranging from Excellent to Fair. While the authors have tried to objectively catalog the merits and problems of each maneuver, these ratings are subjective. Adjectival ratings were assigned as follows:

Excellent. In the evaluated aspect, the maneuver is the best (or tied for best) of all of the ESC effectiveness maneuvers studied. In the evaluated aspect, a maneuver assigned an excellent rating was capable of adequately demonstrating a vehicle was, or was not, equipped with an ESC capable of satisfying NHTSA's minimum effectiveness criteria.

Good. In the evaluated aspect, the maneuver is substantially better than fair but not the best of ESC effectiveness maneuvers studied. In the evaluated aspect, a maneuver assigned a good rating was still

capable of demonstrating a vehicle was, or was not, equipped with an ESC capable of satisfying NHTSA’s minimum effectiveness criteria.

Fair. This maneuver has a substantial problem for this evaluation factor. In the evaluated aspect, the maneuver was unable to adequately demonstrate each vehicle in this study was, or was not, equipped with an ESC capable of satisfying NHTSA’s minimum effectiveness criteria.

Table 5.
Summary of Maneuver Scores.

Maneuver	Maneuver Evaluation Criterion		
	Ability to impose a high level of severity	Is repeatable and reproducible	Considers lateral stability and responsiveness
Slowly Increasing Steer	Good	Excellent	Good
NHTSA J-Turn	Excellent	Excellent	Fair
NHTSA Fishhook	Excellent	Excellent	Fair
Modified ISO 3888-2	Fair	Fair	Good
Constant Radius Turn	Good	Fair	Good
Closing Radius Turn	Good	Excellent	Fair
Pulse Steer	Good	Excellent	Good
Sine Steer	Fair	Excellent	Excellent
Increasing Amplitude Sine	Excellent	Excellent	Excellent
Sine with Dwell	Excellent	Excellent	Excellent
YASR	Excellent	Excellent	Excellent
Increasing Amplitude YASR	Excellent	Excellent	Excellent

DEFINITION OF SPINOUT

As previously mentioned, one of the primary objectives of this study was to develop a test, or suite of tests, capable of determining whether a vehicle is equipped with ESC. Although ESC is designed to intervene in under- and oversteer situations, NHTSA’s discussions with representatives from the automotive industry and ESC manufacturers indicate the primary benefit of this technology is oversteer mitigation.

With respect to maneuver development, use of a spinout definition presents an important implication. Effective ESC is expected to prevent spinout. A precise definition of spinout is necessary to recognize the influence of an effective ESC

Recommendations to NHTSA

While evaluating vehicles with their handling maneuvers, the Alliance experimenters incrementally increased steering wheel angle magnitude until the final heading of the test vehicle appeared to be at least 90-degrees from the initial direction of travel. This termination condition was chosen because it offered a good combination of high maneuver severity (a terminal oversteer state had been achieved) and high face validity (a vehicle will likely have departed from the road by the time it reaches 90-degrees from its original path), while avoiding unnecessary abuse of the test vehicles and tires. The authors agree with the Alliance-recommended termination criterion, and believe that if it was taken as a definition of “spinout,” it could potentially provide a means of determining whether a vehicle is equipped with ESC. However, since NHTSA does not presently possess a means of accurately and absolutely determining a vehicle’s final heading angle with respect to it’s initial, pre-maneuver path, use of this criterion is not feasible at this time. Therefore, an alternative definition of spinout was deemed necessary.

NHTSA Definition

Perusal of the data generated with the four Alliance handling maneuvers and two NHTSA yaw acceleration steering reversals revealed an important trend. In all cases, the yaw rates of the tests that ultimately produced final headings greater than or equal to 90-degrees from the initial paths remained high long after the handwheel had been returned to zero (i.e., after completion of the maneuvers’ respective steering inputs). The authors surmised that if the time the steering wheel returned to zero was taken to be t_o , that comparing the yaw rate of a vehicle at $t_o + x$ seconds to that vehicle’s peak yaw rate could provide a measure of “unresponsiveness” due to terminal oversteer using the following equation:

$$\text{Percent } \dot{\psi}_{Peak} = 100 * \left(\frac{\dot{\psi}(t_o + x)}{\dot{\psi}_{Peak}} \right)$$

where,

$\dot{\psi}_{Peak}$ = first local yaw rate peak produced
after the second steering reversal

$\dot{\psi}_{(t_o+x)}$ = yaw rate at x seconds after completion
of a maneuver's dynamic steering inputs

If this method could be defined in a way that was equally relevant and applicable to all light vehicles, it could be used to identify spinout with high accuracy and certainty. Furthermore, determining whether the spinout criteria had been satisfied could occur immediately after a particular test was performed on the test track, and would require only simple post-test calculation. However, this definition required two key pieces of information: (1) time x , and (2) the value of percent yaw peak that constitutes a spin out.

This technique offers two benefits: (1) it quantifies the severity of a vehicle's tendency to maintain high levels of rotation over time, and (2) it represents a way by which each vehicle could be directly compared against its peers.

Timing Most Relevant to Predicting Spinout

Relating a vehicle's yaw rate at $t_o + x$ seconds to its peak yaw rate is a way of objectively identifying loss of control due to oversteer. This is accomplished by identifying the point after which it is not likely the vehicle will be able to respond to the driver's handwheel input. The handwheel angle has been returned back to zero, but the vehicle continues to rotate about its vertical axis. Specifying a time is important because it makes the distinction between phase lag and loss of control. While the correlation between a mild loss of control and vehicle safety is not presently known, loss of control due to skidding has been a contributing factor to thousands of single vehicle crashes and fatalities each year.

Five time intervals were used to determine the time for which yaw rate data, when compared against its previously established peak value, was most useful in determining whether the vehicle's final heading was greater than or equal to 90-degrees from the initial path. These times were 1.0, 1.5, 2.0, 2.5, and 3.0 seconds, each measured from completion of the maneuvers' respective steering inputs.

A logistic regression model, known as the SAS Genmod procedure, was used to determine how well the percentage of peak yaw, measured at different time intervals would predict the trial outcome, represented by a binary response variable (spin, no

spin). Separate analyses at five different time intervals using two different models were computed. The first model included only the percentage of peak yaw. The second model added vehicle type. Generally, the fit to the data was worse when the vehicle type was included in the model. Therefore, it was concluded that including vehicle type in the model was not necessary, and a more general simple model was used.

When reviewing the data output by SAS, it was important to consider two factors: (1) if the probability of the chi-square analysis (the Chi-Square p-value) is less than 0.05, there is better than a 50-50 chance that percent of peak yaw rate can predict the final heading of the vehicle will be ≥ 90 degrees from its initial path; and (2) the confidence intervals containing the estimated probability of the final heading being ≥ 90 degrees from the initial path can contain values both less than and greater than 0.5 (50 percent probability). For each time increment, consideration of these two factors helps to demonstrate the different regions of model output uncertainty.

The results for the different time intervals were compared, and it was determined that the percentage of peak yaw measured 1.0 second after the beginning of the trial provided the best predictions of outcome. Specifically, it had only one of eleven selected points of percentage of peak yaw for which the outcome was highly uncertain (i.e., the confidence intervals containing the estimated probability of the final heading being ≥ 90 degrees from the initial path included values both less than and greater than 50 percent). All longer time intervals had more points associated with high uncertainty.

Percentage of Peak Yaw Rate Most Relevant to Predicting Spinout

Figure 10 presents a series of curves that model how well the percent of peak yaw rate was able to predict the probability of the vehicle's final heading being ≥ 90 degrees from the initial path for each of the time intervals considered.

Ideally, the shape of each curve would be comprised of a simple step function. As the percent of peak yaw angle increased, the probability of final heading being ≥ 90 degrees from the initial path would remain at zero until a critical percent of peak yaw angle had been achieved. At this point, the curve would step to "1", indicating the probability of final heading being ≥ 90 degrees from the initial path would change from zero to 100 percent in a binary manner. After the

critical percent of peak yaw angle had been achieved, the probability of final heading being ≥ 90 degrees from the initial path would remain at one for all higher percent of peak yaw angle values.

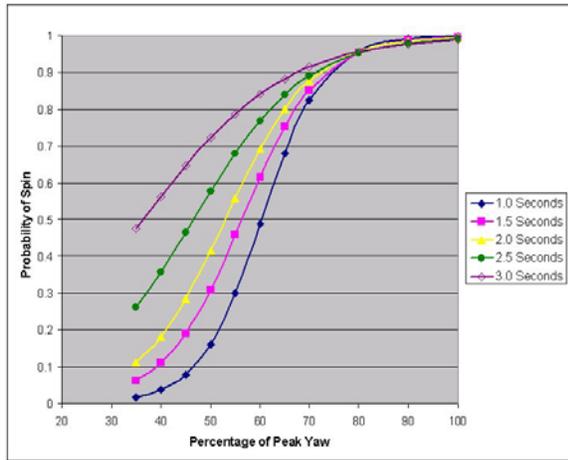


Figure 10. Percent of peak yaw vs. probability of final heading being ≥ 90 degrees from the initial path.

Clearly the curves presented in Figure 10 are not ideal, but the fact that their respective slopes tend to be less steep as the amount of time after completion of the maneuver's steering inputs had occurred is important. This is particularly true for the data where the percentage of peak yaw values were greater than 50 percent.

In the case of the output at time $x = 1.0$ second, one region of uncertainty was found: when the percent of peak yaw angle was 60 percent (i.e., the confidence intervals containing the estimated probability of the final heading being ≥ 90 degrees from the initial path included values both less than and greater than 50 percent). With percentages of peak yaw < 60 percent, for this time interval, the confidence intervals only contained estimated probabilities less than 50 percent. Conversely, with percentages of peak yaw > 60 percent at time $x = 1.0$ second, the confidence intervals only contained estimated probabilities greater than 50 percent.

In summary, despite a small sample size and lack of repeated tests, a logistic regression modeled with SAS was able to estimate the probability that percent of peak yaw rate can predict whether a vehicle's final heading will be ≥ 90 degrees from its initial path. Comparison of data collected 1.0, 1.5, 2.0, 2.5, and 3.0 seconds after completion of the maneuver's respective steering inputs indicate the model is the least uncertain when time $x = 1.0$ second are used.

Using time $x = 1.0$ second data, the model produced one region of uncertainty (60-percent of peak yaw rate), whereas the other four times produced three regions of uncertainty.

FUTURE WORK

The objective of this study was to isolate a small number of maneuvers capable of demonstrating whether a vehicle is equipped with an effective ESC. In the next research phase, NHTSA will use a reduced set of maneuvers and a much greater sample of vehicles. Specifically, the data generated in NHTSA's 2005 research efforts will be used to validate, and refine, NHTSA's spinout model.

Although ESC is intended to combat excessive under- and oversteer, NHTSA's 2005 research efforts will emphasize only the evaluation of oversteer mitigation effectiveness. The reasons for this are twofold: (1) oversteer mitigation is believed to reduce more crashes than understeer mitigation, and (2) make best use of available Agency resources. NHTSA believes that quantifying under- and oversteer mitigation effectiveness will require multiple maneuvers, and at this time NHTSA does not believe it has identified a maneuver capable of effectively quantifying understeer mitigation. To embark on a test program that endeavors to evaluate a large number of test vehicles while simultaneously developing maneuvers capable of quantifying understeer mitigation was not deemed feasible.

Maneuver Reduction

Of all the test maneuvers used in this study, only four received "excellent" ratings for each of the three maneuver evaluation criteria: the Increasing Amplitude Sine (0.7 Hz), Sine with Dwell (0.7 Hz), and both 500 deg/sec YASRs. Of these maneuvers, the Sine with Dwell maneuver was particularly effective in exciting excessive yaw with low steering angles. It is believed this occurred because the maneuver increased the opportunity of the yaw responses to "catch-up" to the respective steering inputs before the handwheel angle was returned to zero. Interestingly, although the YASR maneuver is quite capable of producing spinouts, the more favorable overall results seen during Sine with Dwell testing indicate the maneuver is not optimal.

In certain Sine with Dwell tests, peak yaw rate occurred before the steering reversal occurs (after the 500 ms pause), yet the handwheel angle data presented previously in Table 4 showed the maneuver was the most effective in producing spinouts. This

indicates that simply reversing direction of steer at maximum yaw rate does not necessarily maximize the yaw response of the vehicle.

Due to the lower yaw responses when the direction of steer was reversed at maximum yaw rate, and the fact that the YASR (500 deg/sec) was as, if not more, effective than the IAYASR (500 deg/sec), NHTSA will be discarding the later maneuver in favor of a new iteration. The magnitudes of the initial and countersteer handwheel angles associated with this new maneuver are equal, however there is an additional pause before the second steering reversal occurs, as shown in Figure 11.

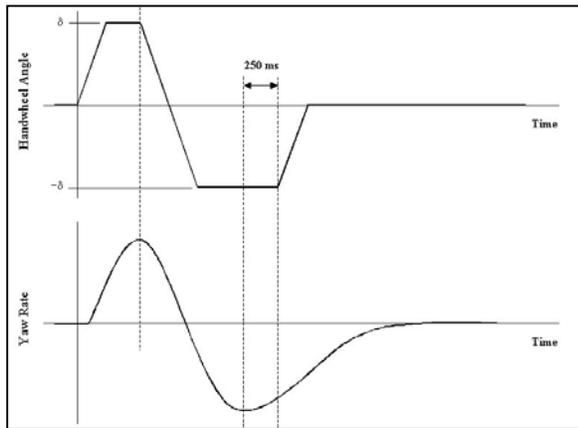


Figure 11. Yaw Acceleration Steering Reversal with Pause handwheel input description.

This combination may provide NHTSA with a maneuver possessing the good adaptability provided by test-dependent, yaw acceleration based steering reversals, but with greater ability to induce excessive yaw due to a 250-ms pause (i.e., conceptually identical to that provided by the Sine with Dwell maneuver). All Yaw Acceleration Steering Reversals with Pause maneuvers will be performed using 500 deg/sec handwheel ramp rates.

Table 6 presents the final, reduced text matrix NHTSA intends to use to evaluate ESC effectiveness in 2005. Note that in the Handwheel Angle Increments column, " δ_{max} " is defined as: (1) the handwheel angle capable of producing a spinout, or (2) the greater of either the handwheel angle capable of achieving a lateral acceleration of 0.3g multiplied by a scalar of 6.5, or 270-degrees.

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Table 6.
NHTSA's 2005 ESC Effectiveness Test Matrix.

Maneuver	Steering Frequency (Hz)	Steering Ramp Rates (degrees/sec)	Handwheel Angle Increments (degrees)	Maneuver Entrance Speed (mph)
Increasing Amplitude Sine	0.7	N/A	45 to δ_{max}	50
Sine with Dwell	0.7	N/A		
YASR	N/A	500 deg/sec		
YASR with 250 ms pause	N/A	500 deg/sec		
Slowly Increasing Steer	N/A	13.5 deg/sec	Linearly increases from 0 to $\delta_{0.55g}$	50 (constant speed)

REFERENCES

- [1] Forkenbrock, G.J., Garrott, W.R., Heitz, M., O'Harra, B.C., "A Comprehensive Experimental Examination of Test Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover – Phase IV of NHTSA's Light Vehicle Rollover Research Program," NHTSA Technical Report, DOT HS 809 513, October 2002.
- [2] Forkenbrock, G.J., Garrott, W.R., Heitz, M., O'Harra, B.C., "An Experimental Examination of 26 Light Vehicles Using Test Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover – Phases VI and VII of NHTSA's Light Vehicle Rollover Research Program," NHTSA Technical Report, DOT HS 809 547, October 2003.
- [3] Forkenbrock, G.J., O'Harra, B.C., Elsasser, D., "A Demonstration of the Dynamic Tests Developed for NHTSA's Light Vehicle Rollover Research Program – Phase VIII of NHTSA's Light Vehicle Rollover Research Program," NHTSA Technical Report, DOT HS 809 705, August 2004.
- [4] Forkenbrock, G.J., Garrott, W.R., "Testing the Rollover Resistance of Two 15-Passenger Vans with Multiple Load Configurations," NHTSA Technical Report, DOT HS 809 704, June 2004.

ACTIVE SAFETY SYSTEMS CHANGE ACCIDENT ENVIRONMENT OF VEHICLES SIGNIFICANTLY - A CHALLENGE FOR VEHICLE DESIGN

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ABSTRACT:

ESP, the Electronic Stabilization Program, was offered by Volkswagen and AUDI, because predictions showed a high potential for injury mitigation through accident avoidance. This encouraged both companies, to offer ESP for most of their vehicles, beginning with the Audi A2/A3 and VW Golf. Adding ESP would make the vehicles more expensive. The decision to offer ESP was a courageous one, especially in the A2/A3 and Golf segments where price was and is a major consideration for customers. So it was clear that the accident performance of vehicles equipped with ESP had to be very carefully and thoroughly studied by Volkswagen and AUDI accident research teams.

The result of this research exceeded expectations. The accident research teams had to increase their projections with every new study. Today, it can be stated that ESP is the most effective safety measure after the safety belt, even more effective than the airbags.

The main figures are: ESP, provided by Volkswagen and AUDI, can prevent 80% of all skidding accidents. This means that ESP has a high potential to prevent roll-over accidents. There is an additional potential of ESP, because it will change pole-side-impact into pole-frontal-accidents. This is still a dangerous accident, but much less dangerous than pole-side-impacts. If only the avoidance effect of ESP is taken into account, it can be stated from accident experience (not projections) that more than 80% of all skidding accidents can be prevented by ESP. This is a new dimension, if compared with passive safety. While a passive safety measure can prevent injuries, ESP prevents

the accident from occurring. The driver does not realize that he just avoided a situation, that might have been fatal without ESP. In Germany, this finding would mean that 35% of all vehicle occupant fatalities could be prevented: Not just reduced to minor injuries, but actually prevented. Secondary effects of injury mitigation, as mentioned before not taken into account. So 35% is a lower limit of the expected effect.

These findings show that the future development of vehicle safety will be driven by accident avoidance much more than by injury mitigation. Rating systems of passenger vehicles should take this into account. Regulation, compliance testing, and rating systems like the different international NCAP organisations should also take this into account.

Accident avoidance is always the better solution. Future development should reflect this widely accepted philosophy. NCAP-ratings should make sure that a „best pick“ is really a best pick based primarily on accident avoidance and not just with respect to injury mitigation.

INTRODUCTION

Vehicle safety during all stages of product development and production has always been common practice at Volkswagen. Accident research in combination with the development of products that offer high levels of passive and active safety has a high priority in this process.

Since passive safety has been the focus of vehicle development in the past, remarkable progress has taken place in this field that has led to a high standard of performance in passenger vehicles. Vehicle designs have brought about dramatic decreases in the injury risk to vehicle occupants.

Over the last several years, advances in electronics have increased the feasibility of vehicle systems that help the driver to prevent accidents. Early examples of such systems are ABS (Antilock Braking System) – in more recent vehicles, ESP (Electronic Stabilization Program) can be seen as the most notable example of such active safety measures. In contrast to passive safety measures, such systems do more than just reduce the overall risk of injury. They influence accident diversity and thus change the requirements for future safety developments.

To gain more knowledge about those changes, the VW group operates teams of experts, consisting of engineers, physicians and psychologists to analyse accidents involving recent VW vehicles. Accident reconstruction provides initial information regarding the probable cause of the accident.

In addition to these activities, representative accident data from several national and international sources is analysed in depth to gain a better appreciation of the incidence of potentially critical situations.

Several studies from various groups involved with traffic safety have proven the benefits of ESP in preventing accidents. Thus, as a result of the increasing size of the portion of the vehicle fleet equipped with ESP, the distribution of different accident types will change significantly in the years to come. Brake assist systems (BAS) are a further example of features that will influence real-world accident scenarios. Comparable effects can be expected from other active safety systems expected to be introduced in passenger vehicles over the coming years.

These changes in accident scenarios give reason to re-think recent test configurations and new test-methods that are currently under discussion. Accident research will have to answer the question,

if current methods are able to handle future tasks and bring about an increase traffic safety.

This paper will offer an overview of, how the benefits of these new systems must be taken into account during the discussion of future regulations and consumer testing. ESP performance will bring about positive changes which can already be observed in Germany. This should be a starting point of a general discussion regarding future goals.

GIDAS ACCIDENT DATA

The analyses in this paper are based on data supplied by GIDAS (German In Depth Accident Study). The advantages of this database are two-fold: (1) the number of cases is high enough to provide statistically significant results, and (2) each case is documented in great detail, permitting in-depth-analyses where required.

GIDAS is a unique project involving the German government and the motor vehicle industry. The cornerstone of the GIDAS-project was laid in 1973 and based on the recognition that official statistics were not sufficient to answer important questions that arise during accident research. For this reason, the German Federal Highway Research Institute (“Bundesanstalt für Straßenwesen”, BASt) initiated a project, in which interdisciplinary teams analysed highway accidents from a scientific perspective – independent of the objectives and needs of law enforcement. The project underwent an important change in 1985, when the choice of the accidents for detailed analysis began to follow a random sampling plan.

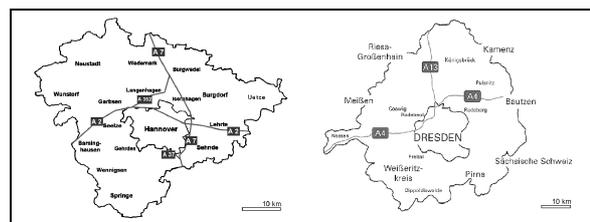


Figure 1. GIDAS Research Areas in Dresden and Hanover.

A second major improvement took place in 1999 when GIDAS was expanded to include cooperation with BASt and the German Association for Automotive Technology Research (“Forschungsvereinigung Automobiltechnik e.V.”, FAT). For this purpose, a second team was established at the Technical University of Dresden. Currently, the sampling criteria are as follows:

- road accident

- accident site in Hanover City and County or Dresden City and County
- accident occurs when a team is on duty
- at least one person in accident injured, regardless of severity

The data collected is entered in a hierarchical database. Depending on the type of accident, each case is described by a total of 500 to 3,000 variables, e. g. accident type and environmental conditions (record Umwelt), vehicle-type, mass, drive train and the type of road it was on (record Fzg), the age, size, hours on the road and injury data for all persons involved (record Persdat and Verlob). Each accident is reconstructed in detail including the pre-collision-phase. Available information includes initial vehicle and impact speed, deceleration as well as the collision sequence.

This database is representative of German national accident statistics, whereby severe cases are slightly over-represented. The database that Volkswagen accesses currently contains as many as 19,300 cases, involving 34,400 vehicles and 49,500 people, 26,700 of which were injured.

SINGLE CASE ANALYSIS AT VW-GROUP-ACCIDENT-RESEARCH

The Volkswagen Group formed one brand research teams at AUDI in Ingolstadt and another at VW in Wolfsburg. One reason to initiate brand accident investigation was the lack of accident data for newer vehicles. Figure 2 shows the phase-in of new models into the GIDAS database. Statistical analysis of accidents with newest models can only be performed if the number of cases in the database is sufficient to provide reliable results. The example of the VW-Golf, one of the top sellers in the German market, shows that this process takes about 5 years.

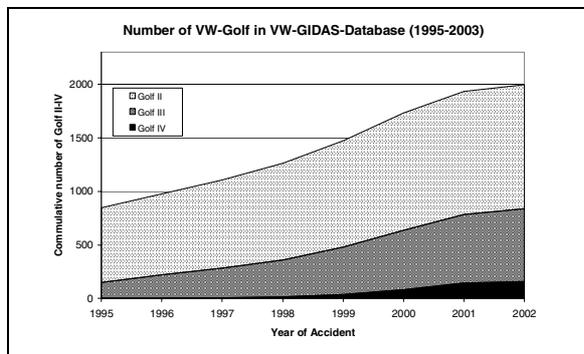


Figure 2: Number of VWGolf Models in GIDASData

This leadtime means that the potential for technical improvements based on real-world accident data would be delayed by at least 5 years. These teams consist of engineers, physicians and psychologists. The multi-disciplinary nature of the teams permits a comprehensive understanding of the accidents investigated. These accident investigations also include a technical analysis of vehicle structure and suspension as well as a complete reconstruction of the accident sequence, including the medical analysis of injuries and the injury causing factors as well as a detailed understanding of accident causation through physical and psychological analysis of the accident scene and in-depth interviews with the persons involved. The basic elements of such accident research are shown in figure 3.

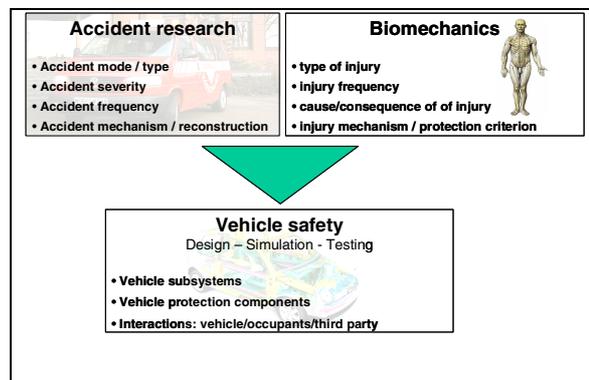


Figure 3. Accident Research at Audi and Volkswagen

To help guarantee the best data quality, both teams are on call 24 hours a day, seven days a week to allow an timely on-scene investigation and documentaion of evidence and debris.

LATERAL AND FRONTAL POLE COLLISIONS

In 2002 in Germany approximately 25% of all passenger car fatalities were attributable to pole impacts (2002: 1577 deaths, 9636 severe injuries). The majority of this accident type shows a stereotypical course of events in which the driver first loses control of the vehicle and after skidding with the vehicle rotating around the z axis a lateral pole/tree collision follows at the side of the road. The cause of the “loss of control” is often driver inattention.

The consequences of such accidents are dramatic as indicated by the incidence fatalities. From a technical perspective, the side structure of any passenger vehicle must be viewed as that part of a passenger vehicle having the smallest deformation space, as much as vehicles width is necessarily limited. Only limited deformable structures with a

limited capacity to absorb impact energy can be provided. Figure 4 shows a comparison between the deformation space available in frontal and lateral structures of a passenger vehicles.

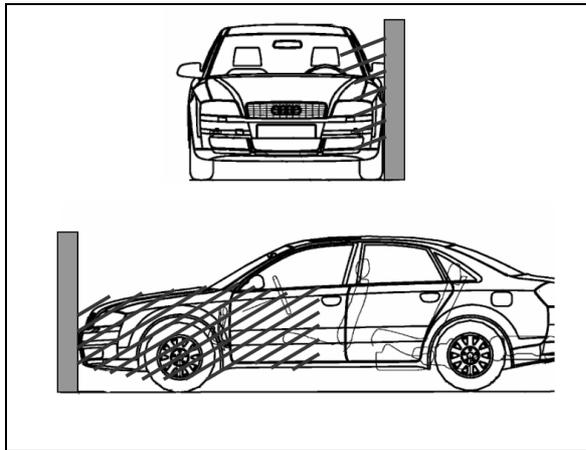


Figure 4. Deformable Areas in frontal and lateral Collisions.

In lateral pole collisions, the distance between occupant and impacting pole is less than 30cm. It is within the narrow confines of this space in which energy absorption and moderate occupant acceleration combined with sufficient survival space to be accomplished in order to minimize the risk of injury. This conflict between energy absorption through deformation and survival space is easier to resolve in frontal impacts where more than 1m space is left between the bumper and the occupant's head. So much more structure can be used to optimize the deceleration process. In frontal impact situations considerably more deformable structure can manage a significant part of the impact energy. In addition, restraint systems optimize occupants kinematics and help to absorb additional energy.

Despite these physical limitations, this collision type has been the focus of vehicle design for many years, in order to decrease the injury risk of lateral collisions. These efforts resulted in remarkable increases in levels of vehicle safety by improving lateral strength together with the introduction of additional safety equipment such as side airbags in the thorax region and curtain airbags. Consumer testing and legislation helped to encourage these improvements with which an optimized level of passive safety has been achieved.

It must be noted that this accident type represents a challenge for safety design. Figure 5 depicts the risk of head injury in lateral and frontal pole impacts.

Both tests were performed with the same vehicle type. In the frontal impact test a Hybrid III-Dummy was used, in the lateral test a EuroSID side impact dummy was selected.

Figure 5 shows head acceleration over time in a 29km/h 90° lateral pole impact and a 35 km/h full frontal pole impact. Considering the amount of kinetic energy involved, the frontal impact can be seen as the more severe event because the impact velocity is significantly higher than the speed in the lateral configuration. Two physical characteristics highlight the difference between these accident types:

- given the lower impact energy, the peak head acceleration is significantly higher than in the frontal impact.
- the time between impact and peak acceleration is much shorter than in frontal impacts.

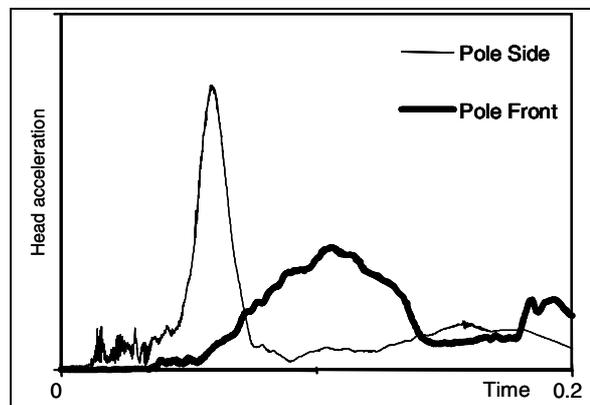


Figure 5. Head Acceleration in Pole to Side and Frontal Pole Collisions.

The first characteristic results from a direct contact of the occupants head with the impacting pole. In this particular example a head airbag was between head and pole which reduced occupant injury risk. The risk of injury associated with such contacts can only be mitigated if the vehicle is equipped with airbags that help protect the head.

The second characteristic indicates that the time to deploy side airbags is very short in comparison with the time available for a front airbag to deploy.

In a frontal pole test at 35km/h, the vehicle is moderately deformed and experiences moderate deceleration. With the exception of the lower extremities, occupants usually do not have contact with vehicle structures. The restraint system (airbag, safety belt, knee padding) can decelerate the passenger over a longer distance than side structures can in side impacts.

Figures 6 and 7 show the deformation of the test vehicle in the frontal impact test. At maximum crush the compartment is completely intact. Figures 8-10 show the vehicle structure in the lateral test configuration. The deformation is more severe. The intrusion into the compartment indicates a comparatively high risk of injury for occupants within the impact area.



Figure 6. First Contact between the Frontal Structure and the Pole.



Figure 7. Maximum Deformation of the Frontal Structure.

In a side impact with a pole at 29km/h the occupant on the struck side is in a free flight with 29km/h against a rigid obstacle. Considering that the door structure cannot be completely crushed, the distance remaining for occupant deceleration is approximately 0.1-0.15m (pelvis, abdomen, chest) and a little bit more for the head. The restraint systems (airbag, padding) have only this small distance available in which to absorb the occupant's kinetic energy. The deceleration phase must be complete within 40-50ms. Up to 40ms the vehicle has moved approximately 0,3m. The deformation phase ends 0.15s after initial contact with an intrusion of appr. 0.5m.

The severity of these side pole impacts and their risk for the occupants is evident. The ability of passive safety measures to reduce this risk is limited by the lack of space as mentioned above.

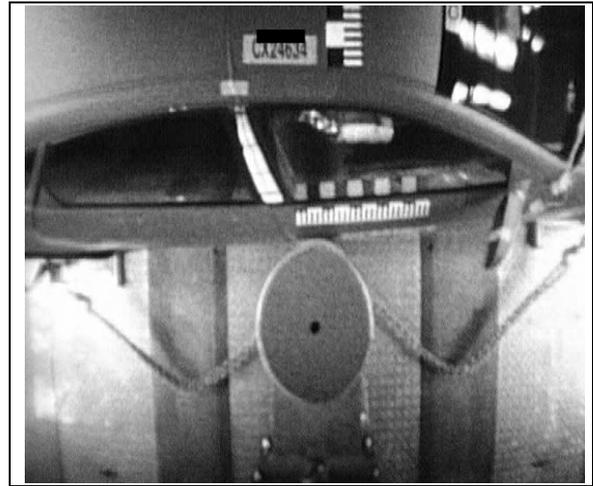


Figure 8. First Contact between the Pole and the Door

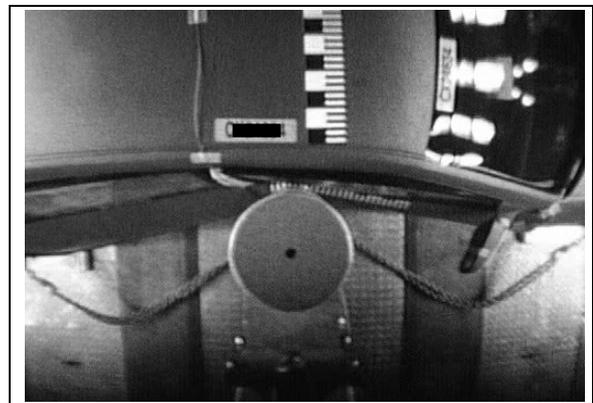


Figure 9. End of Occupants Deceleration.



Figure 10. Maximum Intrusion in the Pole Test

INFLUENCE OF ESP ON ACCIDENT DIVERSITY

In Germany the number of fatalities decreased dramatically during the last decade as shown in figure 11. This continuing trend is strongly influenced by efforts to increase traffic safety by improving the passive safety of passenger vehicles.

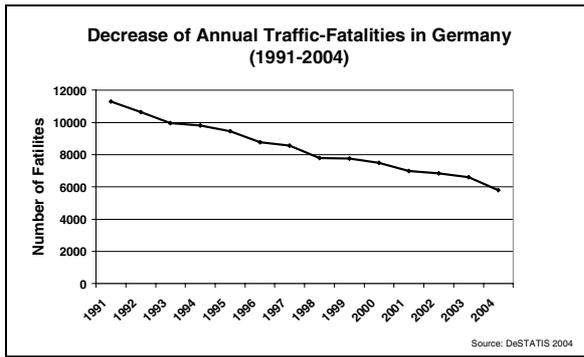


Figure 11. Decrease in Traffic-Fatalities in Germany 1991-2004.

The latest prognosis for fatalities in 2004 in Germany indicates a reduction of approximately 13% as compared to 2003. The absolute number of fatally injured passenger vehicle occupants decreased from 3774 in 2003 to approximately 3300 in 2004. The number of all accidents during this period did not change significantly indicating that technical measures in passenger vehicles can take credit for a significant share of this trend.

After ESP emerged in 1995 as a optional feature in larger and more expensive vehicles, VW decided in 1998 to make ESP available for a majority of its models. Thus ESP is becoming a standard feature in a large number of vehicles in the companies' model lines. This increasing numbers of ESP-equipped vehicles within the fleet in several European markets is shown in Chart 12. The highest share of ESP in new vehicles can be observed in Germany where about 64% of all passenger vehicles sold in 2004 were equipped with ESP.

It is important to note that the influence of ESP is just beginning to become apparent in accident statistics. New vehicles with ESP represent only a small share of the entire fleet in which ESP is still comparatively rare. This is also true for the side impact head airbags passive safety systems. Thus typical accident configurations addressed by ESP will remain quite relevant in the next years to come.

ESP must be viewed as an initial step for the transition from passive to active safety in passenger vehicles. Several industry and insurance studies and analyses by highway administration institutes have already demonstrated the apparent remarkable ability of ESP to reduce the incidence of fatalities in "loss of control" accident situations. The efficiency of the system was stated to be about 50% with respect to the reduction of severe accidents

and up to 80% in reducing accidents in which skidding was the initiating event.

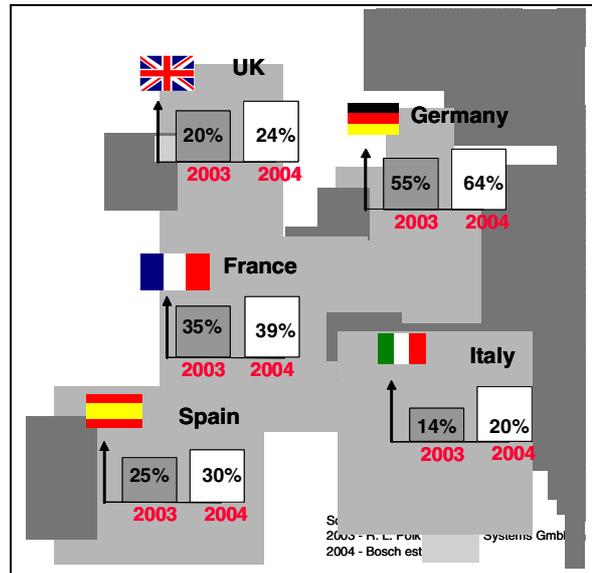


Figure 12. Equipment Rates for ESP in Europe as estimated by Robert Bosch AG.



Figure 13. Influence of ESP on Skidding.

These estimates are confirmed by a retrospective analysis of real-world accident data. The first estimates of the effectiveness of ESP were performed by VW in 1998. These findings were exceeded dramatically by field observations after system introduction.

The beneficial effect of ESP appears to have been verified. The next step must be to quantify its influence and then to project this on the universe of accidents to be expected in the future.

Figure 14 shows the diversity of passenger vehicle accidents in rural areas by accident type when only accidents with injuries to occupants of passenger vehicles of at least MAIS 4+ are considered. The analysis is based on VW-GIDAS data. The chart indicates that in Germany "Leaving the Road" is

the most dangerous accident category that is, responsible for more than 50% of all severe injuries in rural areas.

This results include accidents involving specific infrastructural characteristics of German rural roads that are often lined with trees. In many of these “Leaving the Road” accidents, the initial event led to a pole impact with the consequences described above.

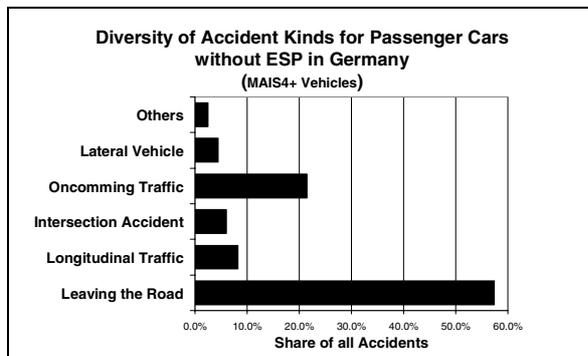


Figure 14. Diversity of Rural Accidents for Vehicles without ESP and MAIS4+ Injured Occupant.

Assuming that ESP is able to prevent 80% of all accidents initiated by skidding, the equivalent of “Loss of Control,” the diversity of the accident universe would change dramatically. Figure 15 depicts the results of a calculation which shows this diversity, if all passenger vehicles were equipped with ESP. To point out the overall effect of ESP, the denominator was the same as in figure 13. Thus the change in the percentage of a particular accident type can directly be interpreted as the potential of ESP to prevent these accidents.

As expected, the predominant influence of ESP can be observed in “Leaving the Road” accidents. But all other kinds of accidents were also influenced.

The potential in absolute terms is shown in detail in figure 16. ESP, according to this analysis, is able to prevent accidents in all different kinds. The resulting reduction of all MAIS4+ accidents is about 40%, thereby confirming the results of other studies.

Taking the frequency of the different accident types into account, collisions with oncoming vehicles are the second most accident type and significantly influenced by ESP. These collisions often result in lateral collisions with oncoming vehicles when the passenger vehicle goes into a skid.

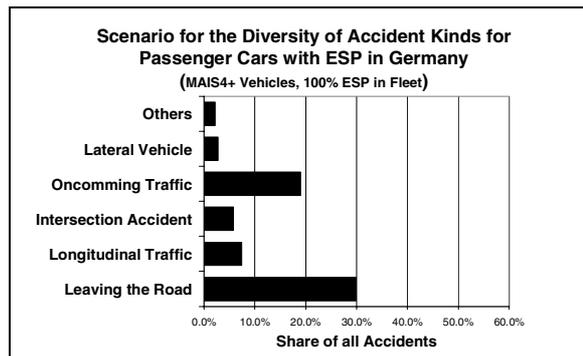


Figure 15. Resulting Scenario for MAIS4+ Accidents if the German Fleet is Equipped 100% with ESP

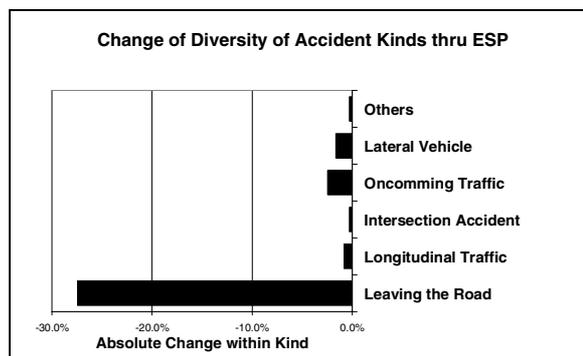


Figure 16. Changes of Accident Diversity through ESP.

A further question to be answered is whether ESP will also influence the diversity of collision opponents for passenger vehicles. These changes would directly influence the performance parameters related to vehicle design. Figure 17 shows the same type of diagram as figure 14 with the diversity of the collision opponents in the initial collisions. Accidents involving passenger vehicles in rural areas in which occupants were injured with a severity of at least MAIS 4+ were analysed.

The chart provides the reason why pole impacts were the focus of passive safety measures in the past and are still being discussed in the context of improved passenger vehicle safety. Nearly 40% of all accidents in Germany in which passenger vehicle occupants sustain severe injuries MAIS 4+ must be attributed to pole impacts.

But does this Chart reflect the safety level of modern passenger vehicles? It does not. The data is derived from a fleet in which both recent active and passive safety systems, such as ESP and side impact head airbags are still a rarely installed.

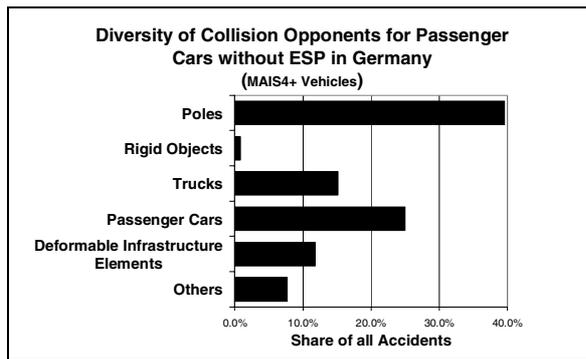


Figure 17. Collision Opponents of Passenger Vehicles in Accidents with MAIS4+ Injuries to Vehicle Occupants.

Figure 18 shows the calculation assuming a 100% ESP equipment rate within the entire fleet. The proportion of pole impacts decreases significantly. The technical effect of ESP reduces the yaw angle of the vehicle by producing an opposing momentum via the brakes. Therefore it can be assumed that the pole impacts prevented must be principally lateral collision configurations, because these collisions are most likely to occur in ESP-relevant situations.

A detailed analysis of the data confirms this assumption. Lateral pole impacts are reduced by approximately 70% based on this scenario, while frontal impacts are reduced by approximately 30%. The proportion of lateral pole impacts decreases from 56% of all pole impacts to 39% of the remaining pole impacts. More than 50% of all pole impacts would have been completely prevented if ESP were installed in the entire fleet.

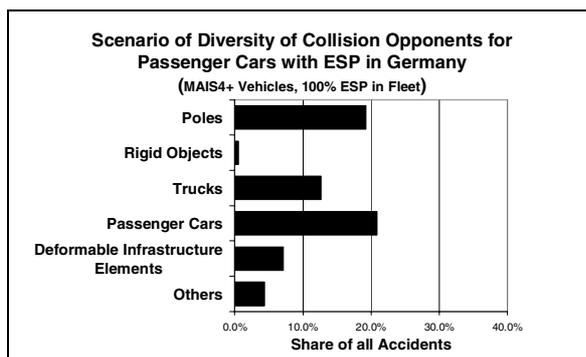


Figure 18. Resulting Scenario for MAIS4+ Accidents if ESP is installed in the Fleet by 100%.

The remaining pole impacts are dominated by frontal collision configurations in which recent vehicles are able to offer optimized passive safety levels to protect vehicle occupants.

Furthermore figure 19 shows the overall effect of ESP, which by preventing skidding, will, of course, influence all other collision constellations and opponents. Combined with the findings from figure 16 that shows a significant effect on collisions with oncoming vehicles, the reduction of collisions with other motor vehicles shown in figure 19 can be interpreted as a reduction of another severe accident configuration: side collision with oncoming vehicles. These accidents are less frequent as compared to pole impacts but they are of comparable severity. Thus ESP can be viewed as a system that focuses on the severest accidents and contributes significantly to their prevention.

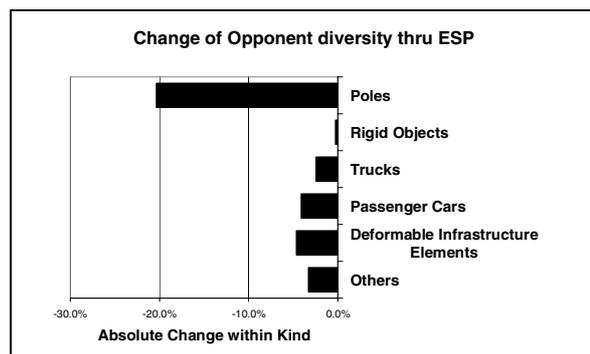


Figure 19. Changes of Opponent Diversity with ESP.

ESP AND PASSIVE SAFETY MEASURES

To underline the significant benefit that ESP can have on vehicle safety, a comparison is made between the effect of ESP and the effect of safety belts, structure and airbags. For this reason, 4 scenarios were defined and evaluated with the help of GIDAS data:

Scenario	Belted Occupant	Vehicle manufactured 1995 or later	Airbag available	Number of cases in GIDAS
1	No	No	No	Ca. 1 000
2	Yes	No	No	Ca. 13 500
3	Yes	Yes	No	Ca. 630
4	Yes	Yes	Yes	Ca. 1 800

Figure 20. Scenarios to estimate effectiveness of passive safety measures.

These scenarios are used to describe the effectiveness of measures.

Scenario 1 ⇒ 2 Safety belt effectiveness in vehicles manufactured before 1995

Scenario 2 ⇒ 3 Structural enhancement for belted occupants in vehicles manufactured before 1995 and in vehicles manufactured later

Scenario 3 ⇒ 4 Airbag effectiveness in vehicles manufactured in 1995 or later for belted occupants

To compute effectiveness values, injury risk in these scenarios was computed:

RISK REGARDING MAXIMUM AIS OF ALL INJURIES OF PERSON	UNBELTED PASSENGER CAR OCCUPANTS IN CARS MANUFACTURED BEFORE 1995 (NO AIRBAG) SZENARIO 1	BELTED PASSENGER CAR OCCUPANTS IN CARS MANUFACTURED BEFORE 1995 (NO AIRBAG) SZENARIO 2	BELTED PASSENGER CAR OCCUPANTS IN CARS MANUFACTURED 1995 AND LATER (NO AIRBAG) SZENARIO 3	BELTED PASSENGER CAR OCCUPANTS IN CARS EQUIPPED WITH AIRBAG AND MANUFACTURED 1995 AND LATER SZENARIO 4
AIS 0..6	100,00%	100,00%	100,00%	100,00%
AIS 1..6	77,78%	44,21%	38,10%	36,43%
AIS 2..6	35,81%	12,31%	8,10%	7,00%
AIS 3..6	15,58%	4,16%	2,06%	1,59%
AIS 4..6	8,93%	1,82%	0,79%	0,51%

Figure 21. Risk of MAIS-categories within the scenarios.

In all categories, injury risk decreases. The categories AIS 5..6 and AIS 6 were not included, because the number of cases is too small and thus the statistical significance poor. Note that 0.79% of 630 cases (AIS 4..6 in scenario 3) represents 5 cases. The effectiveness is derived from these figures:

EFFECTIVENESS REGARDING MAXIMUM AIS OF ALL INJURIES OF PERSON	UNBELTED TO BELTED OCCUPANTS BEFORE 1995 SZENARIO 1 VERSUS SZENARIO 2	BEFORE 1995 TO AFTER 1994 FOR BELTED OCCUPANTS SZENARIO 2 VERSUS SZENARIO 3	BELTED WITHOUT AIRBAG TO BELTED WITH AIRBAG AFTER 1994 SZENARIO 3 VERSUS SZENARIO 4
	Effectiveness of Belt	Effectiveness of Structure	Effectiveness of Airbag
AIS 1..6	43,2%	13,8%	4,4%
AIS 2..6	65,6%	34,3%	13,5%
AIS 3..6	73,3%	50,3%	22,8%
AIS 4..6	79,6%	56,5%	35,5%

Figure 22. Effectiveness of belt, structural enhancements and airbags.

These figures show a clear picture of the relevance of passive safety measures:

The most important safety measure is the safety belt. Vehicle occupants who do not buckle up live in a much more dangerous world than those who use their safety belts. The second most important safety feature is vehicle structure. In all cases the increased benefit from scenario 2 to scenario 3, relates to the optimized structural behavior of passenger vehicles, manufactured in 1995 and later. Structural effectiveness is less than that of the safety belt, but more than that of the airbag. Airbag effectiveness is still significant, but it is ranked third in this list. The next question is, what about ESP?

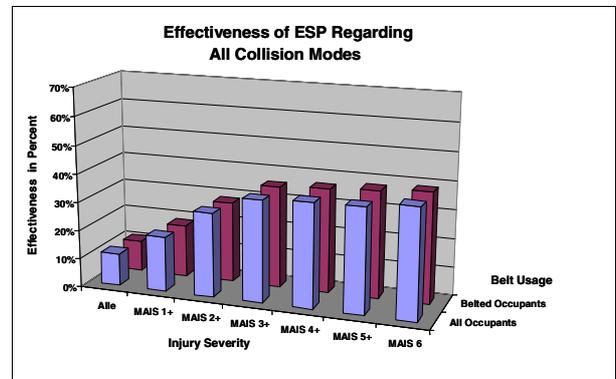


Figure 23. Effectiveness of ESP for occupants with different injury severities.

The effectiveness is nearly the same for belted and for unbelted occupants. The calculation is based on 80% reduction of skidding accidents, as determined by the Volkswagen field study.

Effectiveness of ESP for passenger car occupants				
All collision modes	Belted Occupants	Unbelted occupants	All Occupants	Effectiveness of Airbag
MAIS 0+	10,9%	17,7%	11,4%	0,0%
MAIS 1+	18,4%	22,8%	19,3%	4,4%
MAIS 2+	28,5%	30,4%	29,4%	13,5%
MAIS 3+	35,7%	35,3%	35,6%	22,8%
MAIS 4+	36,7%	35,2%	36,5%	35,5%

Figure 24. Comparison of effectiveness of belt, structural enhancement, airbag and ESP for occupants with different injury severities.

The table clearly answers this question. The effectiveness of ESP is higher than that for the airbag, especially for lower injury severities. The advantage of ESP is that it is independent of restraint use. Crash avoidance is effective for both restrained and unrestrained vehicle occupants. This is not equally true for passive safety measures.

Again, this finding clearly underlines that the level of safety offered by a particular passenger vehicle can only be described properly, if both, passive and active safety measures are taken into account. This computation of ESP effectiveness is conservative and only describes a lower limit of the real effectiveness, because it only takes into account skidding accidents that have been prevented. It is not covered by this calculation that there is a potential of ESP to reduce skidding accident severity by transforming lateral pole impacts into frontal pole impacts. So this computation is still conservative.

To make it very clear, this computation must not be understood questioning the effectiveness of front airbags, on the contrary, these figures show the substantial effectiveness of front-airbags. The message is that ESP is even more effective. As a footnote it should also be noted that enhanced vehicle structures had an even greater effect than front-airbags and ESP. This is often forgotten.

CONCLUSION AND DISCUSSION

ESP is even more effective than airbags.

By ESP, active safety plays the leading role in vehicle safety, more effective than all foreseeable measures of passive safety.

This is the first time that active safety dominates the enhancement of vehicle safety.

It has been shown that there are technical and physical limitations relating to the protection of occupants of passenger vehicles by passive safety measures. Current vehicles have reached a level of passive safety that can only be improved by an inappropriate increase in vehicle weight and associated expense to the customer. Both options lead to other conflicts e.g. fuel consumption.

Active safety measures promise to improve traffic safety by preventing accidents. Ethically they must therefore receive first priority if they have the requisite technical reliability.

The implementation of such systems can have a significant influence on the diversity of accidents as demonstrated by ESP. Thus, views concerning traffic safety must change when the proportion of

such systems in the fleet increases. The latest research results including "In-Depth" accident data indicate that the efficiency of such systems can be predicted. Busch quantifies the effect of different systems in his doctoral thesis [9]. The change of the of the accident mix can be estimated by applying this methodology.

Current discussions on new passive safety test methods do not take these changes into account, e.g. the current discussion on additional lateral pole tests in the US leads in the wrong direction. The accident type sought to be addressed will disappear with the increase in the proportion of the fleet equipped with ESP. The current level of safety is sufficient to assure the functionality of today's passive safety measures. A new test method would interfere with the requirements for those measures and thus increase their cost but the additional benefit to the customer would be marginal. It must be noted that the effects of recently implemented systems both passive e.g. head airbags and active are just starting to influence the accident mix because the current fleet of passenger vehicles is still dominated by vehicles without such systems.

For future advancement of traffic safety all of these factors must be taken into account: ESP is more relevant than front airbag. So a passenger vehicle rating system that neglects ESP or credits it with minor relevance is not reflecting vehicle safety.

New test procedures must focus on the leading injury causing constellations. They must be driven by the objective of optimizing the fleet of cars, currently under production. An uncritical reflection of accident data about older cars will not provide optimum occupant protection for future cars.

REFERENCES

- [1] Löffelholz, Herbert, "Unfallereignisse am Unfallort". In: Bierau, Dieter/ O'Day, James/ Grush, Ernest S.: Erfassung und Auswertung von Straßenverkehrsunfalldaten – FAT Schriftenreihe (54). Frankfurt (Main): Forschungsvereinigung Automobiltechnik, 1986, p. 69-78.
- [2] Scheunert, Dieter/ Sferco, Raimondo/ Becker, Holger, "Unfallforschung – wo liegen Potentiale?", Verband der Automobilindustrie (VDA), "Technischer Kongress 2002", Stuttgart, 21.-22. März 2002.
- [3] Brunner, Horst/ Georgi, Andreas, "Drei Jahre Verkehrsunfallforschung an der TU Dresden", Automobiltechnische Zeitschrift (ATZ), 2 (2003), p. 166-171.

- [4] Busch, Sebastian/ Stanzel, Michael/ Zobel, Robert, "Einsatzmöglichkeiten der GIDAS-Datenbank für Fragestellungen der aktiven Sicherheit", 1. Dresdner Tagung, „Verkehrssicherheit interdisziplinär“, 27.-28. Juni 2003.
- [5] Frank, Peter/ Reichelt, Werner, "Fahrerassistenzsysteme im Entwicklungsprozess", Jürgensohn, Thomas/ Timpe, Klaus-Peter (Hrsg.), "Kraftfahrzeugführung", Berlin: Springer, 2001, p. 71-78.
- [6] Becker, Holger/ Zobel, Robert/ Friedrich, Horst, „Accident Research for Primary and Secondary Safety – a Core Competence of Automotive Technology in the next Century“, IAATM-Conference, Stockholm, 2000
- [7] "Verkehr – Verkehrsunfälle 2002", Fachserie 8 / Reihe 7, Statistisches Bundesamt, Wiesbaden, 2003.
- [8] Becker, Holger/ Donner, Eckart/ Graab, Birgit/ Zobel, Robert, "In-Depth-Erhebungen und Einzelfallanalyse, Werkzeuge zur Verbesserung der Fahrzeugsicherheit im Volkswagen-Konzern", 1. Dresdner Tagung, „Verkehrssicherheit interdisziplinär“, 27.-28. Juni 2003.
- [9] Busch, Sebastian, „Entwicklung einer Bewertungsmethodik zur Prognose des Sicherheitsgewinns ausgewählter Fahrerassistenzsysteme“, Fortschritt-Berichte VDI, Reihe 12 Nr. 588, VDI Verlag, 2005.
- [10] Becker, Holger / Busch, Sebastian / Zobel, Robert, „Methods for the valuation of primary safety measures by means of accident research“, FISITA World-Congress , Barcelona 2004.
- [11] Zobel, Robert, "Head, Neck And Thorax - Benefit from Fleet change and Restraint Systems", 9th EMN Congress, Bukarest 2004.
- [12] Schönbeck, Susanne et al., "Voraussichtliche Entwicklung von Unfallzahlen und Jahresfahrleistungen in Deutschland – Ergebnisse 2004", Bundesanstalt für Strassenwesen – BASt, 2004.

THE EFFECTIVENESS OF ESC (ELECTRONIC STABILITY CONTROL) IN REDUCING REAL LIFE CRASHES AND INJURIES

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Paper number 05-0135

ABSTRACT

ESC (Electronic Stability Control) was introduced on the mass market in 1998. Since then, several studies showing the positive effects of ESC has been presented.

In this study, data from crashes occurring in Sweden during 1998 to 2004 were used to evaluate the effectiveness of ESC on real life crashes. To control for exposure, induced exposure methods were used, where ESC-sensitive to ESC-insensitive crashes and road conditions were matched in relation to cars equipped with and without ESC. Cars of similar or in some cases identical make and model were used to isolate the role of ESC.

The study shows that the positive and consistent effects of ESC overall and in circumstances where the road has low friction. The overall effectiveness on all injury crash types except rear end crashes was 16.7 +/- 9.3 %, while for serious and fatal crashes; the effectiveness was 21.6 +/- 12.8 %. The corresponding estimates for crashes with injured car occupants were 23.0 +/- 9.2% and 26.9 +/- 13.9%.

For serious and fatal loss-of control type crashes on wet roads the effectiveness was 56.2 +/- 23.5 % and for roads covered with ice or snow the effectiveness was 49.2 +/- 30.2%. It was estimated that for Sweden, with a total of 500 vehicle related deaths annually, that 80-100 fatalities could be saved annually if all cars had ESC.

On the basis of the results, it is recommended that all new cars sold should have ESC as standard equipment.

BACKGROUND

The Electronic Stability Control, ESC or ESP, is an on-board car safety system, which enables the stability of a car to be maintained during critical manoeuvring and to correct potential under steering or over steering (1). In a general sense the equipment should eliminate loss of control. Since 1998, when the first mass-produced car with ESC standard equipment was launched, the market for cars with ESC has grown quickly. In Sweden, the proportion of new car sales equipped with ESC has grown from 15% in March 2003, to 69% in Dec 2004.

ESC operates normally with both brakes and engine management. If the car loses control, defined as when one wheel or more is moving faster or more slowly than calculated from the steering input and turning angle, braking is applied to one or more of the wheels, and the engine power might be reduced.

It has been expected, that the ESC will have a significant effect on loss of control type crashes. This effect is expected to have an influence both on the number and the severity of impacts (1), and might also change the orientation of the vehicle prior to impact (2, 3, 4). A projection of the effects based on in-depth data suggests that in 67% of the fatal and 42% of injury only crashes where the driver lost control, ESC would have a probable or definite influence (1). For all injury crashes, the estimated proportion of crashes addressed is 18%, for fatal crashes 34%.

Several studies have been presented, demonstrating the effectiveness of ESC in real life crashes. A Swedish study (5) presented in May 2003 showed that there was a positive influence of ESC, especially in crashes on wet surface or surface covered by ice or snow. The effectiveness ranged between 20% and 40%, all being significant.

Aga and Okado (6) showed that crashes dropped by 30 % to 35 %, and a German study (7) from 2002 showed a similar effect of ESC.

Unsel et al (8) demonstrated a 30% reduction of crashes where the driver was at fault and a 40% reduction of loss of control crashes.

Two American studies have shown major effects of ESC. A NHTSA study (9), preliminary results show a 35% reduction of single vehicle crashes for passenger cars, and for fatal single vehicle crashes with 30%. Corresponding figures for SUVs were 67% and 63% respectively.

Farmer (10) show similar results with a 34% reduction overall of fatal crashes.

Other studies also express positive results (11, 12)

While ABS (anti-locking brakes) also was subjected to high expectations prior to being available, several studies have shown that the effects are minor, or close to none (13, 14). While the crash type distribution has been found to be different for cars equipped with ABS compared to cars without, the net effect is probably less than 5% reduction of crashes with injuries (13, 14). With ESC, the situation seems to be different, with high expectations prior to real life experience but with high and consistent effectiveness in studies of real life crashes so far.

The aim of the study was to:

- Present a method and apply it to estimate the influence of ESC on crashes in Sweden
- Estimate a possible reduction of real life crashes with injuries and for serious and fatal injuries separately.

METHOD

In this study, induced exposure is used to estimate the exposure to crashes for cars equipped and not equipped with ESC. This is an accepted method to use in situations when it is not possible to calculate the true exposure (13, 15, 16). The method is based on the identification of at least one type of event that is not expected to be affected by ESC. For that specific case, the crash number relation between ESC and not ESC would be considered as the true exposure relation. Any deviation from the established basic distribution for crashes not affected by ESC is considered to be a result of the equipment of ESC. The method is also considered to be based on the fact that there are no other differences between cars equipped and not equipped with the system under study (ESC), or any other user related factor that would alter the

expected equal distribution of events and crashes. Both these prior factors are normally complicated to fulfil and control. In the present study, not only type of crash but also the surface condition was used to estimate possible effects. In the purest form, the effectiveness is calculated by

$$E = (A_{ESC} / N_{ESC}) / (A_{nonESC} / N_{nonESC}) \quad (1).$$

Where E is the effectiveness of ESC on crashes sensitive to ESC. A is the number of crashes sensitive to ESC, and N is the number of crashes considered not sensitive to ESC.

The standard deviation of the effectiveness was calculated on the basis of a simplified odds ratio variance (3). While this method gives symmetric confidence limits, the effectiveness is not overestimated. The formula is given below

$$Sd = E (SQR (SUM 1/n)) \quad (2).$$

Where n is the individual number of crashes of each type. The confidence limits are 95%.

A critical part of the method is to choose and identify cars that are identical in every other factor than the presence or absence of ESC. This is in reality very complicated, as ESC is firstly not a random equipment, but has sometimes to be ordered separately or was introduced in a sequence where none of the vehicles of a particular model had ESC, and after a certain date, all had. The third possibility is when a vehicle has ESC as standard equipment on some of the versions of a model range, often linked to other differences. There is no record of ESC equipment kept in the register of vehicles in Sweden. In this study, the focus has been on finding two sets of vehicles, with and without ESC, where ESC was introduced as standard equipment at a certain point in time. The benefits are that the selective bias in picking ESC as option, or choose a car with higher specifications, are avoided. On the other hand, a car with and without ESC has not been subjected to the same conditions otherwise. If the same time is picked for the analysis, the cars without ESC is on average older than cars with ESC, or if the age of the cars is identical, the time at which they were exposed is not the same. It is, however, not impossible to control for these confounders, as the history for the cars without ESC could be analysed as to what happens when the car gets older.

In this study, products mainly from Mercedes-Benz, BMW, Audi and VW were included in the analysis as case cars. The majority of the cars picked would be classified as more upmarket models, but there are some that would be considered as models attracting a wider part of the

market, such as MB A-Class, Audi A3/A4 and VW Passat.

The other critical part of the method is to pick crash types and/or road surface conditions that are considered to be insensitive to the effect of ESC. It is important that this part is done a priori to the analysis. The approach used in this study was to use the results of a European multi centre assessments of where ESC would have an impact (1). In the European multi centre study, expert teams assessed on a number of in-depth studies in a scaling system how much ESC would have contributed. It was found, that crashes in intersections would not have been benefited much by ESC, while other types of crashes would have been affected to a varying degree. Also, lower friction, in this case rain, is a risk factor.

In the present study, rear end impacts on dry surface were considered insensitive, and both wet roads as well as roads with snow and ice were treated separately. The reason for picking only rear end impacts was that it is one of a few crash types that alone on just dry road conditions would constitute enough cases to be used. Logically, it is also a crash type that would not involve much of vehicle handling factors. This is an even more limited crash type than proposed by the study mentioned above, which has the advantage that effects of ESC could be picked up over a more varied set of crash types. A broader set of crash types would have limited the possibility to estimate the overall effect of ESC. The disadvantage by not disaggregating the effects on individual crash types is obvious, but the data set was not large enough to allow such a detailed analysis.

MATERIAL

The data set was constituted by police reported crashes with at least one injured person in Sweden. All crashes from the years 1998 to 2004 was used to select crashes with vehicles from model year 1998 to 2005. All crashes recorded by the police contains at least on injury. From vehicle model codes the car models with electronic stability program (ESC) were specified. Matched controls were identified also by the model codes. The controls were selected to be as close as possible to the case vehicles. In many cases the same model or model platform was used as control. Appendix 1 shows the vehicle models used in this study. In all 1942 crashes with ESC equipped cars were found. The control group contained 8242 crashes. For every crash the road condition, dry, wet or snowy/icy was used together with the collision type. The deformation pattern of the vehicles were also used. The cars used can be seen in appendix 1.

The data set contained fatalities (42 case and 179 controls), severe injury cases (294 case and 1319 controls) and minor injury crashes (1609 cases and 6774 controls).

While police reported crash data is known to suffer from a number of quality problems, none of them is likely to influence the findings of this study to any large degree.

RESULTS

The results are based on the assumption that rear-end crashes on dry roads are not, or only slightly, affected by the presence or absence of ESC. Both ESC vehicles and the selected controls are all equipped with ABS, so there should not be any influence of such a factor.

The results presented were based on a selected sample of control cars. There was also a control calculation performed using all post 1998 car model vehicles and their crash distribution. This control group and the used matched control group show an almost identical distribution of rear end crashes to other crashes, as well as the distribution of crashes on the three road surface types used in this study. The selected and used control group therefore does not seem to differ from the rest of the car population, and the case group does not differ from the control, group in the crash type that is used as the exposure basis (rear end collisions on dry road surface).

In table 1, the calculated effectiveness of ESC for crashes with injuries and for crashes with serious outcome (serious and fatal injuries) are presented. These cases include crashes with unprotected road users. Estimates for crashes only involving car occupants are given separately. It can be seen, that all reductions are significant. It can also be seen, that for serious and fatal injuries for car occupants, the reduction is at least 13% (lower 95% confidence limit). While it is understood that this estimate reflects on the total outcome, ESC is likely to be only relevant for some crash types and for some road conditions.

Table 1.
The effectiveness of ESC on crashes with personal injuries. 95% confidence limits. All estimates are reductions in relation to rear end impacts

All crashes excl rear end	16.7% +/- 9.3%
All crashes excl rear end, car occupants	23.0% +/- 9.2%
Serious/fatal crashes excl rear end	21.6% +/- 12.8%
Serious/fatal crashes, excl rear end, car occupants	26.9% +/- 13.9 %

In table 2, the estimates for single car, oncoming and overtaking crashes are given. It can be seen, that the effectiveness is higher, than for crashes overall. The highest effectiveness is related to single vehicle crashes with serious/fatal outcome.

Table 2.
The effectiveness of ESC on crashes with personal injuries, by crash type. 95% confidence limits. All estimates are reductions in relation to rear end impacts on dry road surface

Single, oncoming and overtaking casualty crashes	31.0% +/-10.2%
Single, oncoming and overtaking serious/fatal crashes	40.7% +/-15.1%
Single serious/fatal crashes	44.4% +/-19.6%

Table 3.
The effectiveness of ESC on crashes with serious and fatal injuries, by road surface. 95% confidence limits. All estimates are reductions in relation to rear end impacts for related road surface

Single/oncoming/overtaking crashes, dry surface	24.8% +/- 26.0%
Single/oncoming/overtaking crashes, wet surface	56.2% +/- 23.6%
Single/oncoming/overtaking crashes ice/snow surface	49.2% +/- 30.2%

In table 3, ESC related crashes for different road surfaces, are given. While the effectiveness on dry surface is not significant, the reduction for serious and fatal crashes on wet and surface covered by ice or snow is large and significant. For the low friction surfaces, the reduction is in the order of 50%. Treated together, the best estimate for all surfaces except dry, is 53+/-18%, demonstrating a minimum of 35% reduction.

A best estimate for fatal outcome in the same type of crashes is also 53%, but with larger confidence limits (+/-45%) as a result of the smaller material.

A separate analysis was made to evaluate if there are any major differences as to where cars with and without ESC has a deformation pattern that differ. This was done for both all crashes, as well as for single vehicle crashes. No difference was found.

DISCUSSION

Electronic Stability Program (ESP) or Electronic Stability Control (ESC) is a new technology, brought into the mass market in 1998. Some studies (1, 2, 3, 4) predicted a positive outcome, but it was not until late 2002 (7) and early 2003 (5, 6), that the first results from real life crashes were reported. At this stage, the results were more positive than expected given the experience with other primary safety systems (13, 14).

Since then, several studies (8, 9, 10, 11 and 12) have demonstrated similar positive results from ESC. While the results have been related to studies with varying selection criteria, study type and effectiveness estimates, all studies show a positive and large effectiveness. Another strength is the fact that the data has been collected in different countries and with different set of vehicles. Still, there is a need to continue to validate earlier results and evaluate long term effectiveness. The amount of studies and the clear and consistent results show, however, that there is no fundamental problem in evaluating primary system effectiveness with robust statistical techniques.

At this stage, evaluations can only be made on the basis that all ESC systems and for all car models, have the same effectiveness. Two studies from the US (9, 10) have been able to separate passenger cars from SUV, but it is likely that there are also other differences that are important. There is a development ongoing in making ESC more sophisticated and covering more situations. This is done without knowing what characteristic of ESC that is mostly safety related, and therefore the understanding of the impact of more sophisticated systems must be done by empirical evaluation of real life crash data.

The method used for this study has been used in many other types of evaluations (13, 14). It is a method that is dependent on a number of assumptions and critical factors. It should be understood, that new vehicle technology is not brought into the market in a way that would guarantee a scientific evaluation. First of all, the

technology is not randomly equipped to vehicles, and there is probably a selective recruitment to such technology. Secondly, in the early stages of implementation, ESC seemed to be brought to the market on more up-market car models, and vehicles in high-performance versions. Attempts have been made in this study to overcome this problem, but there are still some doubts about how the technology is picked up by consumers. The novelty of the technology might even lead to, that drivers of cars with such technology will provoke the system to act, or that there are some behavioural modifications. These phenomena are very hard to control for, but might modify the long-term effectiveness of ESC or similar technologies. In the present study crashes with cars sold as early as 1998 were included, with no detectable difference over the time period.

The method used in the present study, does not allow an analysis on the actual function of the system, and in what sequence of driving it has its potential. Whether ESC works as an intelligent system to warn the driver about low friction, or if it has a direct function in the driver-vehicle loop in critical manoeuvres, either in controlling stability and/or reduce speed, was not possible to study. It could be expected that the functionality of the system has an impact, as for example, ESC insensitive crashes for cars with and without ESC seem to happen with the same distribution over different road surfaces. If ESC was most effective in warning for low friction, it is likely that also other crash types on low friction were affected. This was not the case in this study.

It has been mentioned earlier (2), that ESC could have an effect on the direction and location of impact. A higher proportion of crashes would be expected to be frontal rather than lateral. In this study no such effect could be found.

This study, as well as studies from others, shows clearly that ESC has a very high potential in saving lives and injuries. In this study, the number of crashes where car occupants are severely injured or killed, the effectiveness is over 25%. In crashes that are more ESC sensitive, like single/oncoming/overtaking crashes on wet or icy roads, the reduction is in the order of 50%. This is more than most other safety systems, except from the use of seat belts. If a new technology like ESC was brought into the whole car population, this would have a major impact on the total losses in the road transport system. It is therefore essential, that ESC is brought in as one of the key strategic instruments to fulfil high ambitions in road safety programmes across the world. This was done in Sweden already in 2003, with a firm recommendation to the public. At that stage, the

fitment rate on new cars was 15%. In September 2004, 16 months later, the fitment rate was 58%, and a stronger recommendation was given. In December 2004, the fitment rate on new cars had grown to 69%. This is probably one of the highest in the world. The other Nordic countries have fitment rates varying from 30% to 40% (source Bosch) while for Europe as a whole, there are countries with fitment rates as low as 10%. A strong action from the society, media and consumer groups is probably an important factor. There is at this point no reason not to recommend all consumers to choose a car with ESC, and to advise car manufacturer to only market cars with ESC as soon as possible.

CONCLUSIONS

- ESC was found to reduce crashes with personal injuries, especially serious and fatal injuries.
- The effectiveness ranged from at least 13% for car occupants in all types of crashes with serious or fatal outcome to a minimum of 35% effectiveness for single/oncoming/overtaking serious and fatal crashes on wet or icy road surface.

RECOMMENDATIONS

- Consumers should be recommended to buy cars with ESC, and automotive industry should only market cars with ESC as quickly as possible. Such a policy statement has increased the fitment rate on new cars in Sweden to almost 70% in less than two years.
- Further studies should be made, to validate the results of the present study, and increase the understanding of the mechanism of the improvement.

REFERENCES

- 1 Sferco R, Page Y, Le Coz, J-Y, Fay P. Potential effectiveness of Electronic stability programme (ESP) – what European field studies tell us. ESV paper no 2001-S2-O-327. Amsterdam 2001.
- 2 Zobel R, Friedrich H, Becker H. Crash research with regard to crashworthiness and crash avoidance. Vehicle safety 2000 Conference. I Mech E London 2000.
- 3 Langwieder K, Gwonenberger J, Hummel T. Benefit potential of ESP in real life crash situations involving cars and trucks. 18th ESV Conference. Nagoya 2003.
- 4 Papelis Y, Brown T, Watson G, Holtz D, Weidong P. Study of ESC assisted driver performance using a simulator. University of Iowa. Doc no N04-003-PR.2004.
- 5 Tingvall C, Krafft M, Kullgren A, Lie A. The effectiveness of ESP (Electronic Stability Programme) in reducing real life accidents. ESV paper 261. 18th ESV Conference. Nagoya 2003 and Traffic Injury Prevention Vol 5 p 37-41.
- 6 Aga, M, Okada A. Analysis of vehicle stability control (VSC) 's effectiveness from crash data. ESV paper 541.18th ESV Conference. Nagoya 2003.
7. Breuer J. ESP safety benefits. Daimler Chrysler press presentation. Sindelfingen 2002.
- 8 Unselt T, Breuer J, Eckstein L, Frank P. Avoidance of "loss of control crashes" through the benefit of ESP. FISIA Conference paper no F2004V295. Barcelona 2004.
- 9 Dang J. Preliminary results analysing the effectiveness of Electronic stability Control (ESC) systems. DOT HS 809 790. Washington DC 2004.
- 10 Farmer C. Effect of electronic stability control on automobile crash risk. Traffic Injury Prevention Vol 5:317-325. 2004.
- 11 Langwieder K, Gwehenberge J, Hummel T. International field experiences with electronic stability (ESP) in cars. FISITA Conference. Barcelona 2004.
- 12 Page Y, Curry S. Is ESP effective on French roads? 1st International ESAR Conference. Germany 2004.
- 13 Evans L. Antilock brake systems and risk of different types of crashes in traffic. ESV Conf paper no 98-S2-O-12. Windsor 1998.
- 14 Kullgren A, Lie A, Tingvall C. The effectiveness of ABS in real life crashes. ESV Conf paper no 94-S4-O-07. Munich 1994..
- 15 Evans L. Double paired comparison – a new method to determine how occupant characteristics affect fatality risk in traffic crashes. Crash Analysis and Prevention, Vol 18 No 3, pp 217-227, 1986.
- 16 Hägg A, v Koch M, Kullgren A, Lie A, Nygren Å, Tingvall C. Folksam Car Model Safety Rating 1991-92, Folksam Research 10660, Stockholm, 1992.

APPENDIX CAR MODELS USED

Case car models	Cotrol car models	Case cars	Control
ALFA ROMEO 156	ALFA ROMEO 156	17	45
ALFA ROMEO 166	ALFA ROMEO 166	4	6
AUDI A2		24	
AUDI A3	AUDI A3	63	220
AUDI A3 2	AUDI A4	8	381
AUDI A4		63	
AUDI A4		138	
AUDI A6	AUDI A6	71	380
BMW 3-SERIES	BMW 3-SERIE	117	201
BMW 5-SERIES	BMW 5-SERIE	14	222
BMW 5-SERIES 2		91	
BMW 7-SERIES		2	
BMW X3		5	
BMW X5		16	
BMW Z3	BMW Z3	5	8
BMW Z4		1	
CITROËN C5	CITROËN C5	32	54
FORD MONDEO	FORD MONDEO	29	169
MAZDA 6		24	
MERCEDES-BENZ A-CLASS		129	
	MERCEDES-BENZ C-CLASS 202		86
MERCEDES-BENZ C-CLASS 203	MERCEDES-BENZ C-CLASS 203	19	63
MERCEDES-BENZ CLK	MERCEDES-BENZ CLK	7	35
MERCEDES-BENZ E-CLASS W210	MERCEDES-BENZ E-CLASS W210	423	363
MERCEDES-BENZ E-CLASS W211		52	
MERCEDES-BENZ S-CLASS		2	
MERCEDES-BENZ S-CLASS 2		14	
MERCEDES-BENZ SLK		8	
MINI COOPER		13	47
MITSUBISHI PAJERO	MITSUBISHI PAJERO	13	47
OPEL VECTRA	OPEL VECTRA	8	18
PEUGEOT 206	PEUGEOT 206	84	294
PEUGEOT 307	PEUGEOT 307	49	70
PEUGEOT 406	PEUGEOT 406	11	268
PEUGEOT 607	PEUGEOT 607	20	4
SAAB 9-3	SAAB 9-3	9	111
SAAB 9-5	SAAB 9-5	44	1191
TOYOTA COROLLA	TOYOTA COROLLA	16	96
VOLVO S40/V50	VOLVO S40	27	1638
VOLVO XC90		15	
VW GOLF 4	VW GOLF 4	20	983
VW GOLF 5		15	
VW PASSAT 4	VW PASSAT 4	218	1119
VW SHARAN	VW SHARAN	10	170
VW TOURAN		5	
Sum	Sum	1942	8242

THE EFFECTIVENESS OF PRIMARY SAFETY FEATURES IN PASSENGER CARS IN GERMANY

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ABSTRACT

Based on a large sample of about 690'000 passenger car accidents in Germany for the years 1998-2002 this study investigated in full detail the effectiveness of primary safety features in real world accident behaviour in Germany. In a first part of the paper, a statistically sound methodology for such an investigation is presented, which can be applied to large accident databases. Special emphasis is laid on the question of statistical significance. The main statistical tool to be applied is the method of odds ratios in contingency tables.

After a brief review on existing methods and results in this area in the literature (second part) we apply in a third part the presented methodology to the accident material in order to demonstrate the substantial and statistically significant effectiveness of an Electronic Stabilization Program (ESP) in passenger cars in Germany. These results underline the already available results in the literature and are of great relevance because today already more than 60% of the newly registered passenger vehicles in Germany are equipped with ESP. Additionally to the overall effectiveness of ESP the influence under specific accident situations (like specific road conditions, accidents with fatalities and so on) is going to be investigated.

A further part is devoted to other even more recent primary safety features (like brake assist). Here the situation is much more complicated mainly due to the lack of relevant accident cases, e.g. accidents in which cars with brake assist on board are involved. Especially the car-to-pedestrian accidents are going to be investigated in order to see whether a positive effect of the brake assist can be confirmed.

This study was carried through within the Safety Rating Advisory Committee (SARAC) funded by the European Commission.

INTRODUCTION

The detection and quantification of a possible effect of a primary safety function in the accident behaviour of vehicles is a major area of research in the field of accident analysis. In recent years the possible effect of an Electronic Stabilization Program (abbreviated: ESP) for passenger cars has attracted much attention. ESP aims to prevent a possible instability of a vehicle, when the car does not follow the steering angle. ESP uses single or multiple wheel braking. This forces the car to follow the steering angle as far as possible, due to physical limits. Thus the question is of great importance whether or not ESP is able to prevent to a certain extent the skidding of vehicles and therefore should help the driver not to lose control of the car in critical situations. Even if different manufacturers use different acronyms for their Electronic Stabilization Program, for example Active Stability Control (ASC), Automotive Stability Management System (ASMS), Dynamic Stability Control (DSC), Vehicle Dynamic Control (VDC), Vehicle Stability Control (VSC) or Electronic Stability Control (ESC) are used, we will stay with the abbreviation ESP within this text. The intention of the presented study is to quantify the effect of ESP as an electronic system and the focus is not on possible differences according to make and model.

Of course, ESP is only one of the electronic primary safety functions newly registered cars are going to be equipped with. The Brake Assist (BAS) or the Emergency Brake, Adaptive Cruise Control (ACC), a Lane Keeping Assistant and a Lane Departure Warning System or an Obstacle & Collision Warning System or a Driver Condition Monitoring System are more examples among others.

We do not intend to give a detailed and complete technical description of these electronic safety systems and their working configurations. The main focus we are interested in is the effect of a primary safety function of vehicles on real world accidents. Since skidding accidents are usually rather dangerous for the driver and the other occupants of a car, the potential for an electronic system

which is able to avoid to substantial ratios these types of accidents is of major interest. That is the reason why we mainly focus on the quantification of the effect of ESP. In Germany for example about more than 60 % of the recently registered vehicles already have an Electronic Stabilization Program on board. Since especially the rather severe injuries and fatalities occur in so-called loss-of-control accidents, it could be expected that the avoidance of a reasonable percentage of loss-of-control accidents by ESP is going to result in a substantial reduction of severe and fatal accidents.

Several papers considered the effect of ESP on accidents from different points of view. Aga and Okada (2003) considered the effectiveness of ESP in Japan, while Tingvall et al. (2003) investigated this question on the basis of accident data from Sweden. Recently Page and Cuny (2004) presented a study on the effectiveness of ESP on French roads. Concerning Germany, where nowadays more than 60 % of the newly registered vehicles are equipped with ESP, Zobel (2000), Langwieder et al. (2003) and (2004), Unselt et al. (2004) and Becker (2004) presented rather promising results based on German accident data from different sources. Based on European accident material (EACS data) Sferco et al. (2001) discussed the potential benefits of ESP. Concerning the effectiveness of ESP for single car crashes in the U.S. see Dang (2004). Recently an international comparison of ESP related results has been published by Langwieder (2005).

An overview of primary safety functions and first steps towards an evaluation of such systems can be found in the recent final report of the SEiSS-project of the European Commission.

Some relevant methodological considerations concerning the investigation of the possible effects of primary safety functions can be found in Becker et al. (2004), Busch (2005), Hautzinger (2003), Martin (2003), Otto (2004), Page and Cuny (2004) and Stanzel (2002) among others.

In this paper we intend to present a methodology which could be applied to the investigation of the possible effectiveness of a general primary safety function. Based on a large sample of German accident data for passenger cars for the years 1998-2002 from the German Federal Statistical Office (Deutsches Statistisches Bundesamt) we are going to apply the methodology especially to ESP. The obtained results of the study presented in this paper will underpin the substantial effectiveness of an Electronic Stabilization Program.

After having presented the used methodology from a quite general point of view (which easily allows for transferring the methodology to other primary

safety functions) we are going to consider the effectiveness of ESP in detail. We not only consider accidents but we also have investigated the effectiveness of ESP according to the year of first registration, the age of the vehicle, vehicle size, different road conditions and locations of accidents (e.g. urban and rural) and age or gender of the driver. Another focus is on the most severe risks (i.e. the accidents with fatalities) in order to see the potential benefits from ESP here. It will be seen that the effect of ESP on accidents with fatalities fortunately is rather high. It is worth mentioning that we consider ESP within the presented study as an electronic system and that the results of this paper do not allow any conclusion concerning the effectiveness of ESP for specific makes and models.

In a further section we deal with the problem of misclassification of vehicles and accidents. A misclassification of vehicles occurs when the equipment with the primary safety function is not detected or when a vehicle incorrectly is assigned to be equipped with the safety function. Especially on the basis of mass accident data material it seems unavoidable that these misclassifications of vehicles occur and the effect on the outcomes of an investigation should be considered. The other way round it may also happen that for example an accident is erroneously assigned to be a skidding-accident and therefore one would assume that ESP has some effect on this specific accident which in fact was not possible. We will see in the section on correction of misclassification errors that misclassification of vehicles and misclassification of accidents always lead to an underestimation of the effectiveness of the primary safety function as long as there is in fact a positive effect of the electronic system of interest. This means that the real effectiveness of the primary safety function is always higher than computed from real world accident material, which always contains to a certain percentage errors. In other words this means that one should try to specify the equipment of vehicles and the accident type as proper as possible in order to measure the actual effectiveness of this primary safety function. Moreover we suggest a method which allows for an a posteriori correction of accident data concerning existing misclassifications. The presented methodology is finally applied to the above mentioned accident database and ESP as a primary safety function.

A section on the effectiveness of other primary safety functions as ESP and some conclusions will complete the paper.

STATISTICAL METHODOLOGY

In this section we summarize a reasonable way how to investigate the possible effectiveness of specific primary safety equipment in passenger cars on the basis of accident databases.

In a first step it is necessary to carefully collect accident situations in which the specific primary safety feature of interest is likely to have some effect on the accident outcome (primary safety feature sensitive accident) or has definitely no effect (primary safety feature non-sensitive accident). All other accidents, e.g. accidents for which it is not clear whether an effect for at least one accident-involved party can be expected or not, should be excluded from the further investigation. Together with the selection of accidents we additionally have to assign for each accident (if more than one vehicle is involved in the accident) a car which we will focus on. For the assigned cars we have to be able to decide whether or not these cars are equipped with the primary safety function of interest.

From this selection we end up with a number of cars involved in accidents (for the sake of simplicity also called accidents in the following) for which an effect of the primary safety feature is expected or can definitely be excluded.

The main idea will be to compare the behaviour of the vehicles equipped with a specific primary safety feature and the non-equipped vehicles according to both groups of sensitive and non-sensitive accidents.

This first step already is not very easy to realize on mass accident databases. In such databases typically only a rough classification of accident situations is available. Therefore a clear-cut decision, whether the accident outcome for a vehicle involved in an accident is sensitive or non-sensitive to a specific primary safety feature is impossible. Thus one has to face the problem that the group of sensitive accidents contains cases which in fact have not been affected by the primary safety feature of interest and vice versa. We will see in the case that there indeed is a positive effect of the primary safety function that this dilemma will lead in any case to an underestimation of the effect of the primary safety function. We will come back to this point later on.

The selection of safety function sensitive accidents and accidents which are not affected by the safety function (safety non-sensitive accident for short) also includes the selection of one accident involved vehicle for which the safety function has an expected effect on the accident outcome. This is not a

problem as far as single car accidents are considered, but for most primary safety functions it is advisable to take into account car-to-car crashes as well, since in most types of accidents a collision with another vehicle cannot be excluded.

Having selected sensitive and non-sensitive accidents and corresponding accident involved vehicles moreover one has to decide in a further step, whether or not these cars have been equipped with the safety function. Since mass accident databases usually do not contain this information explicitly, one has to derive it from available car characteristics. In many cases it is possible to obtain the likely equipment from the make and model, the date of the first registration and additional input from the manufacturers. Unfortunately again a clear-cut decision of the question whether a specific car is equipped or not with the safety function is limited. Usually there is the possibility to separate the following three groups

- Cars most likely equipped with the safety function
- Cars most likely not equipped with the safety function
- Cars for which the equipment is not known

One has to exclude the accident cases in which no almost sure information about the equipment can be obtained from the further investigation and one again has to face the problem that for the remaining cases there is a certain rate of misclassification. As before, existing misclassification leads to a further underestimation of the effect of the safety function. We will argue below that up to a certain extent a correction for this underestimation as well as for the underestimation which is due to the misclassification of sensitive and non-sensitive accidents is possible.

Now we have selected accidents which can be split into primary safety function sensitive and non-sensitive accidents and for each accident involved vehicle we know with at least high probability whether the car is equipped or not with the safety function of interest. In order to be able to guarantee a serious investigation on the effect of the primary safety function of interest we have to reduce the number of accident cases once more. The reason is that we are mainly interested in recently introduced primary safety functions. This implies that it typically will be the case that the vehicles contained in the accident database which are equipped with the safety function are only a few years old (e.g. up to 5 years). In contrast the non-equipped cars of course will be to a considerable percentage much older. In order to receive a meaningful comparison one should take into account vehicles with first

year of registration belonging to the same time window. E.g. if we are interested in a primary safety function introduced to the market about 1998/1999 then one should only include accidents from 1999 until today and involved vehicles with year of first registration not earlier than 1999.

Of course there are many other factors which may influence the accident outcome of a crash (e.g. the driver age and gender, the road conditions, the location of the accident, the size of the vehicle and so on). If the accident-involved vehicles equipped or not with the safety function of interest differ substantially in one or more of these factors, then it would become rather difficult to decide whether a possible effect on the accident outcome is caused by the primary safety function or by a confounding factor in which the two groups of equipped and non-equipped vehicles substantially differ. The most ideal situation, i.e. a situation in which we can base the investigation on a huge number of very similar vehicles, driven by similar people in similar locations, which only differ in the equipment with a specific primary safety function, is completely unrealistic. So we have to live with a certain amount of differences in the population of the underlying vehicles. Nevertheless one has to do the best in order to be sure to exclude that a pretended effect of the primary safety function indeed is due to a completely different causation. Therefore in some cases it is advisable to separate the results according to different years of first registration, or to different gender of the driver, or the location of the accident, or the road conditions and so on in order to be able to detect whether there are differences in accident outcome due to one or another factor.

Table 1.
Underlying accident data for an investigation of the effectiveness of a primary safety function

		Primary safety function-sensitive accident		Total
		No	Yes	
Vehicle equipped with primary safety function	No	N_{00}	N_{01}	$N_{00} + N_{01}$
	Yes	N_{10}	N_{11}	$N_{10} + N_{11}$
Total		$N_{00}+N_{10}$	$N_{01}+N_{11}$	N

Furthermore it may be advisable to separately consider light or no injury accidents and severe or fatal accidents.

Finally we end up with accident data which can be represented as is stated in Table 1. On this representation we will base our statistical investigation.

One statistically consolidated method is to base the investigation on the so-called odds-ratio OR, i.e. on

$$OR = \frac{N_{11} / N_{10}}{N_{01} / N_{00}} = \frac{N_{11} \cdot N_{00}}{N_{01} \cdot N_{10}} \quad (1).$$

In the context of the evaluation of the effectiveness of an Electronic Stabilization Program (ESP) the odds-ratio has been successfully been used by Stanzel (2002), Martin (2003), Tingvall et al. (2003), Otto (2004) and Page (2004), see also Hautzinger (2003). An odd in our context is the ratio of the probability of suffering a primary safety function sensitive accident and the probability of suffering a primary safety non-sensitive accident. Since we only take accidents of this two types into account both probabilities add up to 1. The odd is computed for the group of equipped and non-equipped vehicles separately and the ratio of the two odds is the odds-ratio OR.

If one interchanges the role of the variables vehicle equipment and accident sensitivity one could also define an odds-ratio in comparing the odds of the probability that a car with the primary safety function on board is involved in the accident for both groups of primary safety function sensitive and non-sensitive accidents, i.e.

$$OR = \frac{N_{11} / N_{01}}{N_{10} / N_{00}} \quad (2).$$

But this odds-ratio exactly coincides with the odds-ratio from above. Thus it does not matter in which sequence the two variables are considered. Even if one considers the ratio of the odds based on conditional probabilities

$$P(\{\text{Sensitive Accident}\}|\{\text{Equipped Car}\})$$

and

$$P(\{\text{Non-sensitive Accident}\}|\{\text{Non-equipped Car}\})$$

one ends up with exactly the same odds-ratio OR as above.

In case that the primary safety function has some positive effect (note that this effect can only occur in the group of the primary safety function sensitive accidents) the odds-ratio OR is less than one and vice versa (the assertion $OR \geq 0$ holds always true). Since the odds are monotonic function of the corresponding probabilities we have that the

smaller the odds-ratio is the more effective is the primary safety function. That is why the quantity

$$E = 1 - OR \quad (3)$$

is used as a measure of effectiveness of a primary safety function in the literature.

In real data situations (especially when the underlying sample size (i.e. the underlying number of accidents) is low or moderate, one has to avoid that the reason for obtaining an odds-ratio OR which is less than one is only due to statistical fluctuation. This means that we need confidence limits for the odds-ratio OR. Such a confidence interval with a coverage probability of 95% is given for example through the following formula (cf. Agresti (1996), page 24)

$$OR \cdot \exp \left(\pm 1.96 \cdot \sqrt{\frac{1}{N_{00}} + \frac{1}{N_{10}} + \frac{1}{N_{01}} + \frac{1}{N_{11}}} \right) \quad (4).$$

This confidence interval easily carries over to a confidence interval with coverage probability of 95% for the effectiveness E.

The meaning of such a confidence interval is, that we expect with a probability of 95% that the underlying theoretical odds-ratio of probabilities in this interval. Thus, if the upper confidence limit is less than one this would be a statistically significant indication that there indeed is a positive effect of the primary safety function to be investigated. Unfortunately we usually need an at least moderate sample size of accidents in order to obtain statistically significant results.

The effectiveness E can in fact be interpreted in the way that an effectiveness of E means that E·100% primary safety function sensitive accidents could be avoided if all vehicles on the market are equipped with the specific primary safety function. It is a matter of fact, that the Odds-ratio is indeed an approximation of the usual ratio of the following two conditional probabilities

$$P(\{\text{Sensitive Accident}\}|\{\text{Equipped Car}\})$$

and

$$P(\{\text{Sensitive Accident}\}|\{\text{Non-equipped Car}\}).$$

The reason for this matter of fact is that the ratio of the primary safety function equipped and the non-equipped vehicles within the group of accidents non-sensitive to the primary safety function can be viewed as a reasonable approximation to the ratio of both numbers of vehicles on the market.

Of course one could also compute the market share of vehicles equipped and non-equipped with the primary safety function on the basis of *all accidents* in the underlying database. In case that the primary safety function indeed has a positive effect on some accidents this computation will underestimate the share of primary safety function equipped vehicles and therefore will automatically lead to an overestimation of

$$P(\{\text{Sensitive Accident}\}|\{\text{Equipped Car}\}).$$

Finally this in turn implies that a possible effect of the primary safety function of interest is always underestimated.

A comparison on the basis of these two conditional probabilities concerning the effectiveness of a Electronic Stabilization Program (ESP) has been carried through by Unsel et al. (2004).

One might be tempted to think that the above two conditional probabilities coincide with the following ratio, which could easily be obtained from Table 1:

$$\frac{N_{11}}{N_{10} + N_{11}}$$

and

$$\frac{N_{01}}{N_{00} + N_{01}},$$

but this is not the case since Table 1 only contains a selected number of accidents and not *all accidents*, as is really necessary.

If one additionally takes into account the percentage of the primary safety sensitive accidents among all possible accidents then one may compute the reduction among all accidents that are possible if the primary safety functions would have been a standard equipment of all vehicles in a country.

EFFECTIVENESS OF AN ELECTRONIC STABILIZATION PROGRAM

In this section we apply the methodology of the preceding section to a special primary safety function, namely to the Electronic Stabilization Program (ESP). As accident database we use the accident statistics from the German Federal Statistical Office (Statistisches Bundesamt) for the years 1998-2002. This database contains quite a lot of accident data all over Germany. In total for the five years period we have about 690'000 police recorded passenger car accidents available. Not only accidents with at least one injured person are contained in the database but also material damage

only accidents have been recorded in quite a large portion. The recorded passenger car accidents consist of single-car and car-to-car crashes.

The specification of types of accident is rather rough in the database, as is usual for mass accident databases. The German Federal Statistical Office uses seven types of accidents in order to describe the conflict situation which leads to the accident. We decided to use the accidents classified to the type of accident “Driving Accident” as accidents which are most likely to be influenced by ESP (*ESP sensitive accidents*). In the terminology of the Federal Statistical Office a “Driving Accident” is defined as *caused by the driver’s losing control of his vehicle (due to not adapted speed or misjudgement of the course or the condition of the road, etc.)*. In order to be able to compare the accident behaviour of ESP-equipped and ESP non-equipped vehicles we need a control group of accidents which contains only accidents which most likely are definitely not affected by an Electronic Stabilization Program. Here we selected the types of accident “Accident caused by turning off the road”, “Accident caused by turning into a road or by crossing it” as well as so-called “Accident caused by crossing the road (by a pedestrian)” and “Accident involving stationary vehicles”. All the accidents belonging to one of the above mentioned types are assigned to be ESP-non-sensitive accidents. All accidents belonging to the types of accidents “Accident between vehicles moving along in carriageway” and “Other accident” are regarded as accidents which may or may not be influenced by ESP. Since for these accidents a clear-cut decision seems to be not possible we excluded them from the further investigation.

Concerning the names of the types of accidents we stay here with the official English terms published by the German Federal Statistical Office.

Now we come to the accident involved vehicles. Here we choose for all accidents the vehicle of the so-called “guilty driver”. This is the driver of the car which is mainly responsible for the accident.

With the help of several car manufacturers from Europe as well as from Japan we have been able to detect – up to a reasonable degree of reliability – the vehicles which have ESP as standard equipment or not. Makes and models which are equipped to more than 80% with ESP are regarded ESP-equipped vehicles. All vehicles which do not have an Electronic Stabilization Program as standard equipment are stated to be non-ESP-equipped vehicles. In cases in which we are unsure about possible equipment with ESP we excluded the whole accident from the investigation.

In order to include only comparable vehicles in the study we further excluded all accidents in which the vehicle of the guilty driver has been registered for the first time before 1998.

Doing so, we end up in total with a little more than 40’000 German accidents of passenger which we have taken into account for our investigation. This accident data will serve as the basis for the investigation of the effectiveness of ESP. Note that ESP is taken as a system that operates similarly in all cars. Possible differences between makes and models are not considered. The results should rather be considered as average results. The data can be condensed to a 2x2 table (cf. Table 2).

Table 2.
Underlying accident data for an investigation of the effectiveness of an Electronic Stabilization Program (ESP)
All accidents from the years 1998-2002 of passenger cars firstly registered in 1998 or later and only accidents which have been assigned to be sensitive or definitely non-sensitive to ESP and vehicles most likely equipped or not-equipped with ESP

Data Source: German Federal Statistical Office

		ESP-sensitive accident		Total
		No	Yes	
Vehicle equipped with ESP	No	18035	10387	28422
	Yes	9075	3535	12610
Total		27110	13922	41032

From Table 2 we easily obtain an odds-ratio of $OR=0.676$, which leads to an effectiveness E of 32.4% for the Electronic Stabilization Program ESP, which means that at least one third of the ESP-sensitive accidents could be avoided by ESP.

In order to get a deeper insight in the effectiveness of ESP we present in Figure 1 a plot of the effectiveness of ESP for different years of first registration separately. I.e. we created 4 separate tables like Table 2, in which we only included accidents of vehicles registered for the first time in a specific year. Since in 1998 only a rather few number of vehicles equipped with ESP have been registered for the first time we don’t take this year of first registration into account.

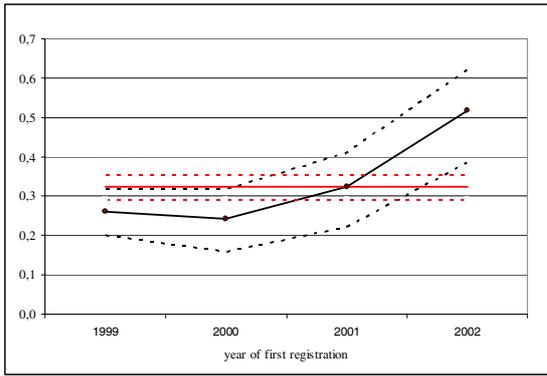


Figure 1. Effectiveness of ESP for different years of first registration (1999-2002) (black) with 95% confidence limits (dotted) and overall effectiveness including 95% confidence limits (red)

It can easily be seen from Figure 1 that the effectiveness of ESP increased with the year of first registration. One might be tempted to conclude from this that the Electronic Stabilization Program has improved over the years. Since we have accident material only for years 1998-2002 at hand we have to be careful. Since we can observe for the most recent vehicles registered for the first time in 2002 only possible accidents during the year 2002, i.e. accidents with a rather new vehicle, in contrast to vehicles registered for the first time in 1998 for which we are able to see potential accidents over a five year period, it might be the case

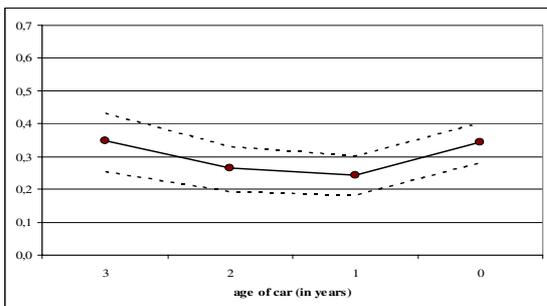


Figure 2. Effectiveness of ESP for different ages of vehicles at time of accident (accidents from the years 1998-2002) including 95% confidence limits

that the effect of increasing effectiveness can be completely explained by a different handling of brand-new and older vehicles. In order to see whether this is the case, we will have a look onto the effectiveness of ESP depending on the age of the vehicle at time point of the accident (cf. Figure 2).

It can be seen that there really is a moderate (but not significant) difference in the effectiveness of ESP according to the age of the vehicle. But it is easily seen that these differences are not able to explain the increase in Figure 1, which underpins, that in fact there is an increase in effectiveness of ESP for more recent vehicles which can't be explained by the age of the vehicle at time of accident. This justifies the assertion that there probably is a technical progress in implementing Electronic Stabilization Programs in vehicles.

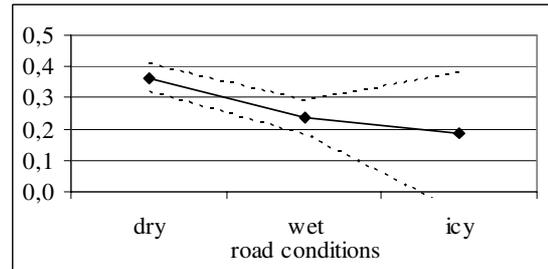


Figure 3. Effectiveness of ESP for different road conditions (accidents from the years 1998-2002) including 95% confidence limits

We further investigated whether there are factors or situations in which ESP-equipped and non-ESP-equipped vehicles differently behave.

Concerning the different daylight conditions (daylight, twilight, darkness) we don't detect any differences in the behaviour of cars equipped or not with ESP, which is accordance with the technical functioning of ESP.

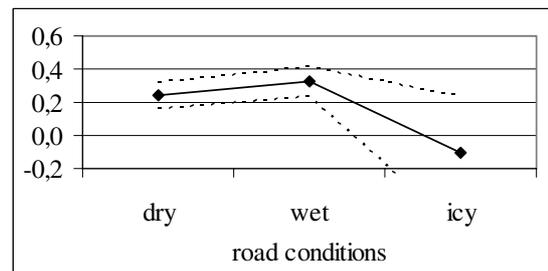


Figure 4. Effectiveness of ESP within built-in areas for different road conditions including 95% confidence limits

In contrast to this we detect some differences depending on the road conditions (cf. Figure 3). Especially it can be seen that the effectiveness of ESP on a dry road is higher than on wet (and icy) roads. Indeed the difference is statistically significant. Let us have a closer look on the effectiveness

of ESP in dependence on the road conditions. We split the accidents according to their location within or outside built-in areas and computed the effectiveness separately (cf. Figures 4 and 5).

The slightly negative odds-ratio in Figure 4 on icy roads within built-in areas is by far not significant. It may be interpreted only in the way that no effect of ESP on the basis of all accidents can be detected for such situations. For special interest in the effectiveness of ESP in such rather rare situations a more specified investigation is necessary.

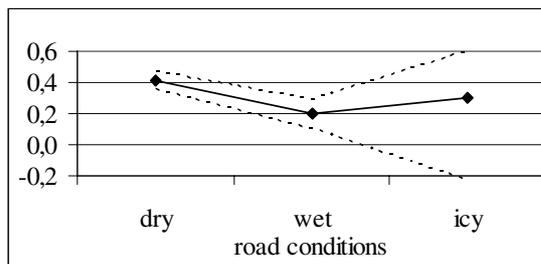


Figure 5. Effectiveness of ESP outside built-in areas for different road conditions including 95% confidence limits

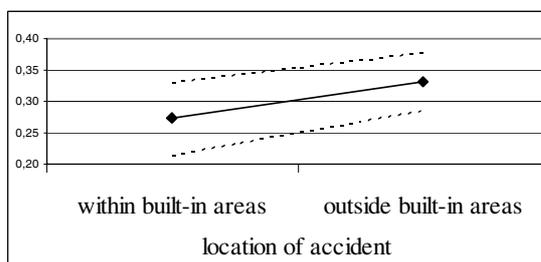


Figure 6. Effectiveness of ESP according to location of the accident including 95% confidence limits

We see from Figures 4 and 5, that the effectiveness of ESP on dry roads is significantly better outside built-in areas where it could be expected that the driving speed is higher than in urban areas and one could on wet roads more easily come into situations, where the physical limits are reached or even exceeded. In contrast, in urban areas one drives usually at lower speed and the risk to skid is higher on wet roads. Because of the lower driving speed one can substantially benefit from a present Electronic Stabilization Program. If one compares the behaviour of ESP for different accident locations (within or outside built-in areas), a substantially, but not significantly, better performance of ESP outside built-in areas can be observed (cf. Figure 6).

Concerning the age of the driver of the vehicle no different effect of ESP shows up, i.e. ESP works well for all age groups of drivers.

Of course it is of great interest to see, how an Electronic Stabilization Program performs for accidents with severe or even fatal injury outcome. The effectiveness of ESP for accidents with fatal injury outcome has proved to be even higher than the effectiveness of ESP regardless the injury outcome of the accident. From the German accident data it is obtained that the effectiveness of ESP for accidents with fatal injury outcome is 55.5% in contrast to an effectiveness of 32.4% over all accidents (including material damage only accidents). The 95% confidence interval for the effectiveness of ESP in fatal accidents reads (31.2% , 71.2%). Nevertheless the potential of an Electronic Stabilization Program to avoid especially extremely severe accidents is rather striking. More than every second fatal driving accident can be avoided by ESP.

Finally let us come back to the driver population and let us compare the effectiveness of ESP for different gender of the driver. Surprisingly it showed up that ESP-effectiveness in women-driven vehicles is significantly better than ESP-effectiveness in men-driven vehicles (cf. Figure 7). A more detailed analysis revealed that this effect is linked to car size, as we will see in the following.

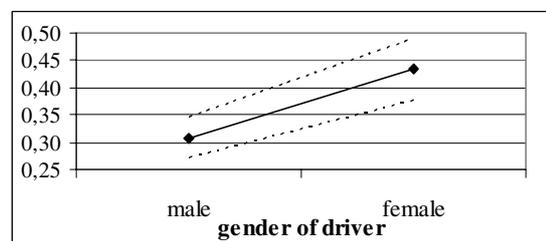


Figure 7. Effectiveness of ESP separately for gender of driver including 95% confidence limits

To this end we investigated within this study as a further factor the size of the vehicle and possible differences in the effectiveness of ESP. It is obtained that the effectiveness indeed differs with the curb-weight of a vehicle (cf. Figure 8). Moreover we see from Figure 8 that especially for smaller cars (curb-weight less than 1100 kg) ESP-effectiveness is rather high and decreases with increasing curb-weight.

In addition to the effectiveness of ESP for different curb-weights in Figure 8 we plotted there the percentage of female drivers within the respective mass categories. It is striking that both curves (ef-

fectiveness of ESP and percentage of female drivers) correspond rather well.

This result strongly suggests that the influence of the gender reported in Figure 7 in fact is an influence resulting from the size of the vehicle. Moreover gender of driver and size of vehicle are obviously (cf. Figure 8) strongly correlated variables and this strong correlation likely leads to the effects presented in Figure 7.

The reason for the high ESP-effectiveness especially for smaller vehicles could be that the incremental safety gain by an Electronic Stabilization Program for those cars is rather high.

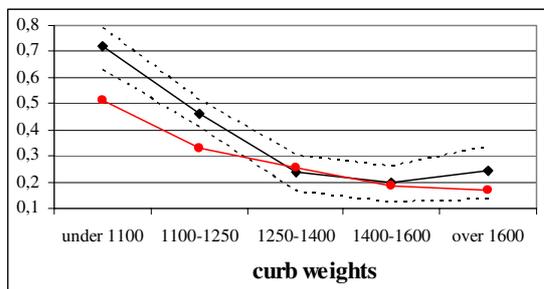


Figure 8. Effectiveness of ESP separately for different curb-weights (in kg) including 95% confidence limits (black solid and dashed lines) together with the percentage of female drivers in the respective curb-weight category (red line)

METHODOLOGY FOR CORRECTION OF ERRORS DUE TO MISCLASSIFICATION

As is already mentioned above we have to face the situation that we can't avoid some errors in classifying accidents into primary safety function sensitive accidents and definitely primary safety function non-sensitive accidents. Especially when an investigation is based on mass accident databases, only a few categories of types of accident exist (e.g. the German Federal Statistical Offices uses seven types of accidents) and the lines are blurred. Concerning the primary safety function ESP we assigned in order to obtain the results of the proceeding section all so-called Driving Accidents to be ESP-sensitive. Of course it is reasonable to assume that a large percentage of the driving accidents are indeed influenced by an Electronic Stabilization Program but it is unrealistic to assume that all driving accidents without any exception have been influenced by ESP. Vice versa it is possible that a small percentage of accidents assigned to be ESP-non-sensitive may have been influenced by the primary safety function. Thus we think that the

assumption that a small percentage p_{acc} of accidents has been falsely assigned to be primary safety function sensitive and the other way round is reasonable. We consider the values 0.05 and 0.10 for p_{acc} .

The same argumentation holds true for the determination whether or not a specific accident involved vehicle has been equipped with the primary safety function or not. Since we usually have to conclude the equipment of a vehicle from the year of registration errors concerning the vehicle equipment are even more likely than erroneously classifying accidents. We assume for the following that the probability that a vehicle of being falsely categorised to the group of vehicles having the primary safety function on board and vice versa is p_{car} . Here values of $p_{car} = 0.10$ or 0.15 seems reasonable.

Table 3. Accident cases corrected for misclassified vehicles (misclassification rate p_{car})

		Primary safety function-sensitive accident	
		No	Yes
Vehicle equipped with primary safety function	No	\tilde{N}_{00}	\tilde{N}_{01}
	Yes	\tilde{N}_{10}	\tilde{N}_{11}

where

$$\begin{aligned}\tilde{N}_{00} &= \frac{(1-p_{car})N_{00} - p_{car}N_{10}}{1-2p_{car}} \\ \tilde{N}_{01} &= \frac{(1-p_{car})N_{01} - p_{car}N_{11}}{1-2p_{car}} \\ \tilde{N}_{10} &= \frac{(1-p_{car})N_{10} - p_{car}N_{00}}{1-2p_{car}} \\ \tilde{N}_{11} &= \frac{(1-p_{car})N_{11} - p_{car}N_{01}}{1-2p_{car}}.\end{aligned}\quad (5).$$

Since the errors in categorising accidents as well as vehicles do not depend on the accident outcome we are able to reconstruct from the observed data in Table 1, to data which do not contain the errors due to misclassification any more. In a first step we correct for vehicle misclassification and obtain (assuming a misclassification rate of p_{car}) Table 3.

In a second step we additionally correct for errors in classifying accidents incorrectly. Assuming a misclassification rate of p_{acc} we obtain the corrected Table 4, which now can be viewed as a table of accidents without miss-specified accidents and vehicles.

Table 4.
Accident cases corrected for misclassified vehicles and accidents (misclassification rates p_{car} and p_{acc})

		Primary safety function-sensitive accident	
		No	Yes
Vehicle equipped with primary safety function	No	n_{00}	n_{01}
	Yes	n_{10}	n_{11}

where

$$\begin{aligned}
 n_{00} &= \frac{(1-p_{acc})\tilde{N}_{00} - p_{acc}\tilde{N}_{01}}{1-2p_{acc}} \\
 n_{01} &= \frac{(1-p_{acc})\tilde{N}_{01} - p_{acc}\tilde{N}_{00}}{1-2p_{acc}} \\
 n_{10} &= \frac{(1-p_{acc})\tilde{N}_{10} - p_{acc}\tilde{N}_{11}}{1-2p_{acc}} \\
 n_{11} &= \frac{(1-p_{acc})\tilde{N}_{11} - p_{acc}\tilde{N}_{10}}{1-2p_{acc}}.
 \end{aligned} \tag{6}$$

It can be shown that the Odds-ratio computed from Table 3 is always smaller than the odds-ratio computed from the not-corrected underlying Table 1 as long as there is a positive effect of the primary safety function, i.e. as long as the odds-ratio from Table 1 is less than one. Furthermore in this case the odds-ratio computed from the completely corrected Table 4 is again smaller than the odds-ratio computed from Table 3 and therefore also smaller than the odds-ratio computed from the completely uncorrected Table 1. In other words this means that in the case where we in fact have a primary safety function which leads to an improved behaviour in accidents which are sensitive to this specific primary safety function we obtain from the underlying Table 1 an upper bound for the true interesting odds-ratio, which is the odds-ratio from Table 4.

Turning to effectiveness this means that the effectiveness obtain from the uncorrected Table 1 underestimates the true effectiveness as long as there in fact is a positive effect of the primary safety function at all. The effectiveness computed from the completely corrected Table 4 may serve as a good approximation of the wanted effectiveness as long as we have specified the misclassification rates properly.

CORRECTION OF MISCLASSIFICATION ERRORS IN THE INVESTIGATION OF AN ELECTRONIC STABILIZATION PROGRAM

In this section we apply the methodology from the preceding section to the special case of ESP. Application of the two correction steps summarized in Tables 3 and 4 together with formulas (5) and (6) leads for the ESP-accident data presented in Table 2 the following corrected accident data (expected numbers with respect to the rates of misclassification)

Table 5.
Accident data for an investigation of ESP corrected for misclassified vehicles (misclassification rate 10%) and misclassified accidents (misclassification rate 10%)

		No	Yes	
Vehicle equipped with ESP	No	20144	10255	30399
	Yes	8614	2019	10633
Total		28758	12274	41032

It can easily be computed that the corrected Table 5 leads to an odds-ratio of $OR=0.46$ and an effectiveness of ESP of 54.0% (in contrast to the effectiveness of ESP of 32.4% obtained from Table 2 directly. It is worth mentioning again that the effectiveness of 32.4% obtained from Table 2 is in fact a lower bound for the effectiveness of ESP. If one agrees with the assumed misclassification rates of 10% for both vehicles and accidents then one should prefer the effectiveness of 54.0% obtained from the corrected Table 5. This effectiveness of 54% means that ESP is able to avoid even more than every second ESP-sensitive accident, which really is impressive. Assuming a misclassification rate of 5% for the accidents and of 10% for the vehicle equipment this leads along the same lines as above to a computed effectiveness of ESP of about 47.5%.

It should be mentioned that one obtains from In-depth accident data (e.g. from the GIDAS accident database) an effectiveness of ESP from about 48.6% (in contrast to an effectiveness of ESP of 32.4% obtained from the mass accident data material used in this study). An explanation could be that the accident classification and the knowledge about vehicle equipment in In-depth databases is much better and that one should compare the results obtained from In-depth data with the computed effectiveness from mass accident data cor-

rected for errors of misclassification. In doing so the obtained effectiveness from corrected mass accident data and from In-depth accident data fit quite well.

Finally Figure 9 compares the effectiveness of ESP separately according to the year of first registration on the basis of uncorrected as well as for misclassification corrected accident data material.

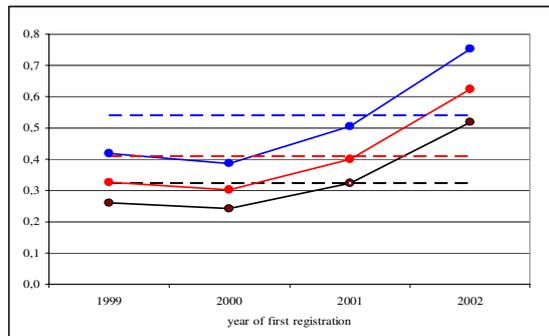


Figure 9. Effectiveness of ESP for different years of first registration (black solid line) and overall according to uncorrected data (black dashed line) and according to corrected data (misclassification rate 5% in red, misclassification rate 10% in blue)

As we have seen above, ESP especially works well for ESP-sensitive accidents with a fatal injury outcome. Above we obtained an effectiveness of ESP for this group of most severe ESP-sensitive accidents of 55.5%. If we correct these fatal accidents along the lines of Tables 3 and 4 together with formulas (5) and (6) from the preceding section for misclassified accidents and vehicles with the same misclassification rate of 10% as above, we obtain an effectiveness of ESP for fatal ESP-sensitive accidents of 77.9%.

If we only take a misclassification rate of 5% for both vehicles and accidents this leads to an effectiveness of ESP for fatal ESP-sensitive accidents of about 65.9%.

EFFECTIVENESS OF FURTHER PRIMARY SAFETY FUNCTIONS

Concerning the effectiveness of a primary safety function that assists the driver of a vehicle to brake as efficient as possible in emergency situations, it seems to be rather difficult to detect the potential effects on accident material from mass databases. Braking is a function which is more or less activated in every accident so we expect difficulties in

separating between types of accidents which are sensitive and definitely not sensitive to braking.

Concerning the effectiveness for example of the Brake Assist (BAS) we most likely have to base the investigations on in-depth accident material. The BAS is constructed in order to reach in an emergency braking manoeuvre the optimum deceleration. It seems to be difficult for a not trained driver to achieve this without the help of an electronic assistant system. Optimum braking in critical situations will lead to the lowest possible speed at the time of the crash, which is of course advantageous for the injury outcome.

From the technical description of the Brake Assist it should be possible to quantify the amount of so-called delta-v reduction which could be reached by the system. Having this information at hand we then need information on injury outcome of accidents depending on delta-v. Such investigations exist and can for example be found in Busch (2005).

The quantification of the effectiveness of a system like the Brake Assist based on real world accident data is still under investigation and will be an ongoing research topic.

An overview of other systems like Adaptive Cruise Control (ACC) or Lane Departure Warning can be found in the SEiSS-report (2005).

CONCLUSIONS

In this paper we presented a statistical methodology which can be applied in investigations based on real world accident data in order to detect and to quantify a possible effectiveness of a primary safety function in vehicles. The methodology is based on a thorough selection and evaluation of accident data in a first step. The main statistical method is the method of so-called odds-ratios in categorical data. This methodology has already been used in other papers in the literature about effectiveness of primary safety functions. Given confidence intervals for odds-ratios allow for the decision whether from accident data observed facts are statistically significant or not.

The presented methodology is then applied to a large sample of German passenger car accidents for the years 1998-2002 recorded by the German Federal Statistical Office. The main focus is on the effectiveness of an Electronic Stabilization Program (ESP). The results demonstrate clearly and significantly that there in fact exists a substantial benefit of ESP. The effectiveness of ESP is quantified for different factors like different road condi-

tions and different locations of the accidents as well as different age and gender of the driver and different sizes of the vehicles. Additionally the effectiveness is presented separately for accidents with fatal injury outcome. The amount of effectiveness of ESP varies over different factors but the main message is that ESP is a successful electronic primary safety function for vehicles.

Moreover the paper contains a proposal on how to correct for misclassification of accidents (primary safety function sensitive or definitely non-sensitive) and vehicles (equipped with the primary safety function or not). Again based on the German data it is demonstrated what the effects of such a correction are concerning ESP. The results show that all misclassifications lead in any way to an underestimation of the actual ESP-effectiveness.

In general it has been found that ESP-effectiveness in all ESP-sensitive crashes amounts at least to 32.4% and may increase to 54.0% by correcting misclassification. The ESP-benefit in fatal accidents is even higher and amounts to 55.5% (based on ESP-sensitive crashes) and may increase to about 77.9%, if for a certain percentage of misclassification is corrected. In summary ESP has again proven to be a most effective safety system and it should be integrated in all modern cars.

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REFERENCES

- Aga M., Okada, A. (2003). Analysis of Vehicle Stability Control (VSC)'s Effectiveness From Accident Data. ESV-paper 541. 18th-ESV-Conference, Nagoya (Japan).
- Agresti, A. (1996). An Introduction to Categorical Data Analysis. Wiley Series in probability and Statistics (New York).
- Becker H., Busch S., Zobel, R. (2004). Methods for the Evaluation of Primary Safety Measures by Means of Accident Research.

FISITA-paper F2004V039. FISITA Conference, Barcelona (Spain).

Busch S. (2005). Entwicklung einer Bewertungsmethodik zur Prognose des Sicherheitsgewinns ausgewählter Fahrerassistenzsysteme. Fortschr.-Ber. VDI-Reihe 12 Nr. 588, VDI-Verlag (Düsseldorf).

Dang, J. N. (2004). Preliminary Results Analyzing the Effectiveness of Electronic Stability Control (ESC) Systems.

U.S. Department of Transportation – National Highway Traffic Safety Administration. Evaluation Note.

Hautzinger H. (2003). Measuring the Effect of Primary Safety Devices on Accident Involvement Risk of Passenger Cars – Some Methodological Considerations. SARAC-paper.

Langwieder K., Gwehenberger J., Hummel T., Bende J. (2003). Benefit Potential of ESP in REAL Accident Situations Involving Cars and Trucks. ESV-paper No. 150. 18th-ESV-Conference, Nagoya (Japan).

Langwieder K., Gwehenberger J., Hummel T. (2004). International Field Experience with Electronic Stability Program (ESP) in cars. FISITA-paper. FISITA-Conference, Barcelona (Spain).

Langwieder K. (2005). Wissenschaftlicher Erkenntnisstand zu ESP / Results of International Scientific Studies Regarding ESP. Conference *10 Years ESP*, Bosch, Berlin (Germany).

Martin J.-L., Derrien Y., Laumon B. (2003). Estimating Relative Driver Fatality and Injury Risk According to Some Characteristics of Cars and Drivers Using Matched-Pair Multivariate Analysis. ESV-paper No. 364. 18th-ESV-Conference, Nagoya (Japan).

Otto, S. (2004). Quantifizierung des Einflusses aktiver Sicherheitssysteme auf die Unfallwahrscheinlichkeit und Identifikation von sicherheitsrelevanten Attributen basierend auf Realunfalldaten. Diplomarbeit, Universität Dortmund.

Page Y., Cuny, S. (2004). Is ESP effective on French Roads. 1st-International ESAR, Hanover (Germany).

SEiSS-Final report (2005). Exploratory Study of the Potential Socio-Economic Impact of the Introduction of Intelligent Safety in Road Vehicles.

Sferco R., Page Y., Le Coz J.-Y., Fay P.A. (2001). Potential Effectiveness of Electronic Stability Programs (ESP) – What European Field Studies Tell us. ESV-paper 2001-S2-O-327. 17th ESV Conference, Amsterdam (The Netherlands).

Stanzel, M. (2002). Analyse von Verkehrsunfällen zur Wirksamkeit des Elektronischen Stabilisierungsprogramms ESP. Mimeo, Volkswagen AG (Germany).

Tingvall C., Krafft M., Kullgren A., Lie A. (2003). The Effectiveness of ESP (Electronic Stability Programme) in Reducing Real Life Accidents. ESV-paper 261. 18th-ESV-Conference, Nagoya (Japan).

Unsel T., Breuer J., Eckstein L., Frank P. (2004). Avoidance of Loss-Of-Control Accidents Through the Benefits of ESP. FISITA-paper F2004V295. FISITA Conference, Barcelona (Spain).

Zobel R., Friedrich H., Becker H. (2000). Accident Research With Regard to Crash Worthiness and Crash Avoidance. Vehicle Safety Conference 2000, London.

INFLUENCE OF CHASSIS CONTROL SYSTEMS ON VEHICLE HANDLING AND ROLLOVER STABILITY

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ABSTRACT

In this paper the influence of active chassis systems, in particular Electronic Stability Control (ESC) and Active Rear Steer (ARS), on vehicle limit handling and rollover stability is examined through vehicle testing. Effectiveness of ESC systems in influencing rollover stability in the National Highway Traffic Safety Administration (NHTSA) dynamic rollover test is first evaluated. Since there is no generally accepted objective and repeatable procedure for evaluating and quantifying vehicle handling as it relates to safety, a process of developing such a test procedure is described. Vehicle handling tests used in the automotive industry are briefly reviewed. The criteria used for selection of maneuvers that show the best potential and can characterize these aspects of handling, which affect safety, are described. A subset of the most promising maneuvers is selected. A step steer maneuver and an open loop maneuver with steering reversal are further developed through simulations and vehicle testing. A preliminary handling metric is described, which balances the aspects of handling influencing safety. Test results for both handling tests are presented, which compare performance of vehicle with ESC and ARS systems enabled to a passive vehicle.

INTRODUCTION

In the last decade, popularity of vehicles with a high center of gravity in the United States, e.g., Sport Utility Vehicles (SUVs), gave rise to increased interest in studying vehicle rollovers and developing active safety systems capable of reducing the probability of this type of crash. While rollovers constitute only a few percent of all crashes, they rank

disproportionately high among fatal crashes. For example, rollovers are responsible for about 25% of all traffic-related fatalities in the USA and about 60% of fatalities in accidents involving SUVs [1]. In response, automakers and suppliers pursue design changes, which could lead to improved rollover resistance without sacrificing utility of vehicles.

Recently, NHTSA introduced a dynamic rollover test as a part of the New Car Assessment Program (NCAP). In the test, a vehicle driven on a dry, smooth and level surface is swerved in a rapid succession in one, then the opposite direction. The steering input supplied by a robot is characterized by high rates and high amplitudes of the steering angle, in order to emulate steering input during an emergency road edge recovery maneuver [2]. It is possible that some design changes made in an effort to improve vehicle rollover resistance in this test may alter vehicle handling characteristics in a way that could adversely affect other aspects of vehicle safety. For example, for a vehicle with high center of gravity, rollover resistance in the dynamic test could be improved by reducing the maximum lateral acceleration or its rate of change. If done indiscriminately, this would limit the cornering ability or responsiveness of the vehicle in emergency maneuvers, both of which are important aspects of safety.

These types of design changes could be achieved with relatively minor effort for a vehicle equipped with an active chassis control system, such as an Electronic Stability Control (ESC). These systems permit vehicle designers to trade off vehicle responsiveness in limit cornering maneuvers against stability by specific tuning of the control algorithm. Since in most rollover crashes, drivers lose control of the vehicle prior to rollover, improving rollover resistance in the dynamic test may not help to prevent rollover from occurring if the improvement is achieved at the expense of emergency handling. The prime goal of this research is therefore the development of a better understanding of vehicle handling and rollover stability, especially for vehicles equipped with active chassis systems. The term

handling is limited here to these aspects of vehicle response to driver steering and possibly throttle and brake inputs, which affects vehicle safety. Since there is no generally accepted, objective and repeatable test procedure that quantifies vehicle handling as it relates to safety, development of such test methodology has become an important goal of this study.

This paper is organized as follows. In the next section the vehicle used for testing, which is equipped with ESC and ARS (Active Rear Steer) systems, is briefly described. Then selected results of NHTSA dynamic rollover tests are presented to illustrate the ability of ESC system to affect vehicle roll stability and yaw response in this test. Subsequently, a brief review of widely used handling tests is given. Criteria for selecting the most suitable handling maneuvers for further development are outlined, followed by detailed development of selected maneuvers. The handling metrics are briefly discussed. Results of vehicle testing in two transient handling tests are presented for a vehicle with ESC and ARS systems. Finally, conclusions are presented.

TEST VEHICLE

The test vehicle used in this study is the Chevrolet Silverado pick-up truck with rear wheel drive shown in Figure 1.



Figure 1. Chevrolet Silverado test vehicle.

The vehicle is equipped to allow safe dynamic rollover and limit handling testing, and to record the data. Specifically, it is fitted with a roll cage, five point harness safety belts and front and rear outriggers. The load rack above the truck bed permits the safe addition of payload to increase the height of the center of gravity and vehicle roll inertia, if necessary. This provides a means of modifying the rollover stability of the vehicle. The vehicle is instrumented with a programmable steering robot to

achieve precise and repeatable steering inputs. Three optical height sensors measure distances from the body to the ground on each side of the vehicle; from these measurements, the true body roll angle with respect to the ground can be derived. Optical sensors placed at all wheel hubs permit determination of wheel lift-off. In addition, suspension deflection sensors allow monitoring of the wheel positions relative to body. The vehicle is also instrumented with an optical sensor measuring longitudinal and lateral velocity with respect to the ground, a steering wheel angle sensor and an instrumentation-grade, six-axis inertial sensor. Two active chassis systems are available on the vehicle: a brake-based ESC system and an ARS system, which can be selectively disabled, if desired. Both of these systems include additional sensors; for example, the rear wheel steering angle, brake caliper pressures at all four corners and wheel speeds are measured. Each active system can be disabled, if desired.

Vehicle performance was also evaluated using a high-fidelity vehicle model, which includes models of active systems and associated control algorithms. The model was validated against the test data. Details of the model are beyond the scope of the paper and are not presented here. In addition to the Chevrolet Silverado, a vehicle with an active stabilizer bar system was used for this evaluation, but the results are not presented here. A detailed description of this vehicle and the simulation model can be found in reference [3].

EFFECT OF ESC SYSTEM ON VEHICLE PERFORMANCE IN DYNAMIC ROLLOVER TEST

In this section the influence of ESC system on vehicle performance in the dynamic rollover tests is discussed and selected test results are presented. As described in the introduction, the dynamic rollover test, also referred to as a fishhook test (since vehicle path in this test has a shape similar to a fishhook), is a severe steering maneuver, which involves a rapid reversal of the steering angle. This induces a large and rapid change in lateral acceleration from a peak value in one direction to the opposite, which heavily excites vehicle roll motion. The vehicle fails the test if it experiences a Two Wheel Lift Off (TWLO) of at least 5 cm (2 in.). The details of the test procedure are given in a NHTSA report [2]. Any active chassis control system, which can reduce vehicle roll angle or lateral acceleration or even the rate of change of these variables during this test, can significantly

affect the outcome. Examples of such systems are the ESC system and active stabilizer bar system. ARS system, which can steer the rear wheels as a function of the front steering angle and speed, has a lesser effect in this test.

The ESC system improves limit handling and stability of the vehicle by correcting severe understeer and oversteer conditions through active control of individual wheel brakes. The system uses the measured steering wheel angle and vehicle speed to determine the desired response of the vehicle in terms of yaw rate and sometimes vehicle sideslip angle or sideslip rate. It then compares the desired states with the measured (yaw rate) or estimated (sideslip angle) ones; when a sufficient discrepancy is detected, the system applies brakes to reduce the difference. By tuning the desired response and the control gains, vehicle designers can affect the balance between vehicle responsiveness and stability. For example, by reducing the magnitude of desired yaw rate or by more aggressive control of sideslip state (at the expense of yaw rate), a more stable response of the vehicle in transient maneuvers can be achieved. This tuning of the system can reduce vehicle rate of response and possibly peak lateral accelerations in fishhook tests, thus improving vehicle resistance to rollover. To illustrate, the results of two Fishhook tests performed at 75 km/h are shown in Figures 2 and 3.

In both cases, extra payload of 400 lb (182 kg) was placed at the load rack to increase tendency of vehicle to tip up during tests. The roll angle was limited to about 15 degrees by outriggers. The ARS system was disabled.

Figure 2. Fishhook test at 75 km/h with ESC system in configuration 1.

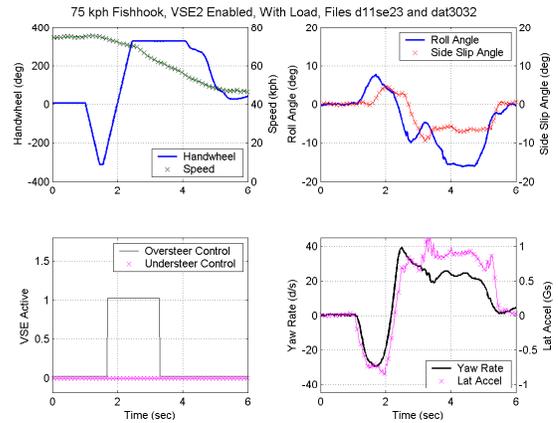
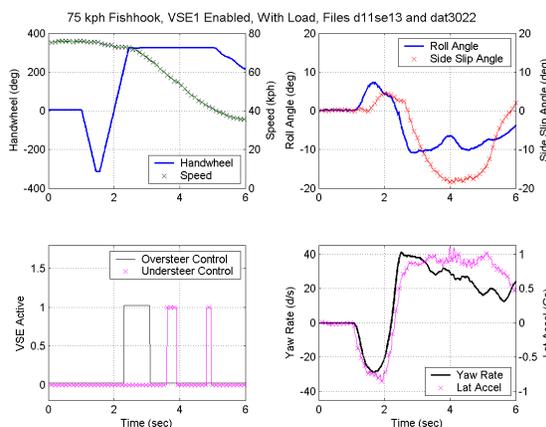


Figure 3. Fishhook test at 75 km/h with ESC system in configuration 2.

In the maneuver illustrated in Figure 2, tuning of ESC system (configuration 1) was representative of many other light vehicles, whereas in Figure 3 (configuration 2) tuning was modified to further restrict oversteer condition by reducing the maximum values of yaw rate and sideslip states. It is seen that during and immediately after the quick transient phase, the ESC 2 system activates earlier and provides correction for a longer period of time. This results in lower vehicle sideslip angle and temporary reduction in vehicle roll angle, yaw rate and lateral acceleration. After the brake intervention subsides, however, the roll angle increases again and is not corrected by the ESC system, since the system is designed to manage yaw plane motion, which is now close to the desired motion. It should be noted that in the same maneuver performed with ESC system disabled (not shown here), the vehicle reached the roll angle corresponding to the outrigger contact immediately after the reversal in lateral acceleration.

It can be concluded that the ESC system has the capability to affect the roll response of vehicles in the Fishhook test, especially in the transient phase of the maneuver, by changing the tuning parameters in the control algorithm. These changes, however, affect vehicle response in the yaw plane by changing yaw rate, sideslip angle and lateral acceleration responses, which are important characteristics of handling. It is therefore desirable to develop a test procedure to evaluate vehicle handling in addition to



rollover propensity, so that vehicle performance and stability in the yaw and roll planes can be evaluated comprehensively.

MANEUVER SELECTION FOR HANDLING EVALUATION

In this section, the process of selecting maneuvers, which could be used to objectively evaluate the handling behavior of vehicles, is described. Vehicle handling is a complex and highly subjective characteristic with many different aspects. In this study, emphasis is on the aspects of handling performance, which affect safety. Of particular interest are the handling properties in the non-linear range of handling and at the limit. There are several reasons for this. First, vehicles often reach the limit handling range in emergency avoidance maneuvers; thus, it is of prime importance in crash avoidance. Second, controlling vehicles at the limit is generally more difficult for a typical driver than in the linear range of handling. Most drivers are accustomed to operating their vehicles in the linear range (normal driving) and do not have experience in controlling vehicles at the limit. Third, since tire forces are limited by surface friction, vehicle handling typically deteriorates as the limit of friction is reached. For example, in handling tests performed by Consumer Union [4] the routine handling score was either better or at least the same as the emergency handling score for all of 141 vehicles evaluated in this publication. Thus, one can expect that good emergency handling guarantees that routine handling would be at least as good.

ASPECTS OF HANDLING AFFECTING SAFETY

The objective here is to establish a test procedure to evaluate and quantify these characteristics of handling, which affect safety. The following are aspects of handling, which in the authors' judgment affect safety:

- **Turning ability** – is an ability of the vehicle to turn sharply in emergency maneuvers; therefore, the maximum lateral acceleration and quickness of achieving it are both important.
- **Graceful degradation at the limit** – there should not be a large or sudden change in vehicle behavior when limit of adhesion is reached. Essentially, this requires a progressive increase in vehicle understeer as lateral

acceleration increases and no rear breakaway, implying small sideslip angle.

- **Predictability** – predictable and progressive response to driver inputs with no or minimal need for corrections. It requires good correlation between the driver input and vehicle response in the entire range of operation. Vehicle response should be well damped with no or minimal overshoot and oscillations (otherwise frequent driver corrections are necessary). Time delays between the input and outputs should be consistent and not too large.
- **Responsiveness** – requires quick response to driver inputs in terms of both initial delay and the total response time and sufficient static gain between the input and the output (e.g. yaw gain).
- **Stability** – not only should the vehicle response to bounded inputs remain bounded, but also certain stability margins should be maintained in both steady state and transient maneuvers. For example, the vehicle should maintain understeer characteristic with limited sideslip angle and no sustained oscillations in transient maneuvers.

It is noted that there exists some overlap among the desired handling characteristics described above. For example, vehicle response must be stable in order to be predictable; reasonably short time delays are required for good responsiveness and predictability and so on.

There exist other characteristics, which are often considered aspects of handling, which are not included in the above list because they either are too subjective or have little effect on safety. These include: on-center steering feel, steering wheel vibration, and steer torque feedback. Ability of the vehicle to reject disturbances, such as due to aerodynamic forces (e.g. side wind), road inclinations or road roughness, is not explicitly included, but it is implied by stability and predictability.

COMMONLY USED HANDLING TESTS

Since there is no general agreement on which handling tests provide the best assessment of handling behavior, many different tests are used by the automotive industry. In general, they may be roughly divided into the following categories:

- Open loop tests, which determine vehicle characteristics in response to specified control inputs.
- Closed loop task performance tests, which determine performance of driver-vehicle combination in a specific driving task.
- Subjective assessment, in which drivers evaluate handling behavior by driving a vehicle over a test track and a set of maneuvers.

The test maneuvers may also be divided into steady state and transient tests, dependent on whether they seek an assessment of steady state or transient properties. Since objectivity and repeatability of test procedure are very important considerations, the subjective assessment, in which both maneuver selection and evaluation are driver dependent, is not considered in this study. From this point of view, closed loop task performance tests have also disadvantages of being driver dependent to some extent and having a tendency to mask the effects of vehicle characteristics since drivers adapt their inputs to vehicle response. However, it is possible to define a reasonably objective index of performance in these maneuvers if measures of task performance are combined with a measure of driver steering effort.

Below, the most common types of handling tests are briefly reviewed. Many of them are either standard maneuvers adopted by SAE or ISO or proposals of standard tests by these organizations.

Slowly Increasing Steer Test (Skid Pad Test)

This test evaluates the steady state handling in both linear and non-linear ranges of operation. There are three forms of this test: constant speed, constant steer, and constant radius. A slowly increasing steer maneuver, in which the steer angle is slowly increased at constant speed, is described in SAE Standard J266 [5]. In another version of the test, a constant steer angle is maintained, but vehicle speed is gradually increased. In a steady state circle maneuver, a constant radius of turn is maintained, while both steering angle and speed are slowly increased [6].

Step Steer Test

A steer input in the form of a step function is applied at a specific speed to produce a specific lateral acceleration. An example is the ISO standard

7401 [7]. This test characterizes transient response of the vehicle, but includes a steady state portion as well. Therefore, quickness of vehicle response to the steering input in terms of yaw rate or lateral acceleration can be quantified. Similarly, variables related to vehicle stability, such as overshoot in yaw and roll responses, can be determined.

Braking in Turn Test

In this test, brakes are suddenly applied in a steady state turn of specified lateral acceleration, as described for example in the ISO/DIS 7975 standard [8]. This test primarily evaluates vehicle stability and predictability, in particular sensitivity of vehicle yaw response to disturbance in the form of braking and associated load transfer.

Dropped Throttle in a Turn

In this test, a vehicle is in a steady state turn with a pre-determined level of lateral acceleration, for example 90% of the maximum acceleration that vehicle can develop on a dry surface. The driver initially applies throttle in order to maintain speed. The throttle is then suddenly released. Similarly to the brake in turn test, this test evaluates vehicle stability and predictability in response to the change in longitudinal tire forces. This test maneuver is detailed in ISO Standard 9816.

Open Loop Test with Steer Reversal

In this test, a steering input is applied which has a pattern similar to that experienced either in a single lane change or a double lane change maneuver. This test demonstrates vehicle response in maneuvers involving steering reversal. This is important, because some vehicles may be stable in a step steer maneuver, but may be difficult to control in maneuvers involving steer reversals, especially when performed at the limit. An example of this type of test is a transient response test with the steer angle being one period of a sinusoid (a pseudo single lane change test) as described in the ISO/TR 8725 proposal [9]. Another example is a pseudo double lane change test proposed by NHTSA [2], in which the steering pattern is an averaged driver steer input in several closed loop test maneuvers. In some variants of the test, the steer input can have rectangular (stepwise) or trapezoidal pattern, which may be more demanding due to the sudden changes in the steer input.

Steer Reversal with Driver in the Loop

In this test, a vehicle is driven through a path determined by cones. The most common types of this test are: single and double lane changes and a slalom. In a single lane change test, the path defined by cones may represent a quick single lane change. A more frequently performed version of this test is the one in which the vehicle is driven straight at a specific speed towards an obstacle (a row of cones) requiring a lane change to either side. The driver is told as late as possible whether to go left or right. The main measure of performance in the test is the shortness of time or distance to the obstacle when the avoidance maneuver can be performed without striking the cones. This is a typical task-performance test, in which the outcome is determined by the driver-vehicle system.

In a double lane change test, the path simulates a maneuver, in which the vehicle quickly changes lanes (e.g. to avoid an obstacle) and then returns to the original lane. The most widely used test procedure is that defined by ISO/DIS Standard 3888 [10]. In this procedure, the course is strictly defined, giving the driver very little freedom in selecting the path. The width of each lane is defined as a function of vehicle width. The main result of the test is the maximum possible speed of entry at which the test can be completed without striking any cones.

In the slalom test, the vehicle is driven as quickly as possible on alternating sides of a series of cones. Large lateral acceleration is generally achieved. This test has been criticized on several grounds. The path of the vehicle and the steer pattern are not likely to occur in real world driving. Furthermore, the comparative ranking of vehicles may depend on spacing of obstacles due to different natural frequencies of yaw and roll modes for different vehicles. This last problem can be mitigated by relating the timing (and spacing) of turns to the natural frequency of the yaw mode, if it exists (e.g. if the yaw mode is not over-damped at the speed at which the test is performed).

Frequency Sweep Test

This test is performed primarily to quantify vehicle handling response to a steer input that covers a significant range of frequencies, with one of the main objectives being obtaining a frequency response characteristic of the vehicle. This can reveal, for example, a resonance frequency in vehicle

yaw response, which may lead to instability under harmonic steer input at that frequency. Quickness of vehicle response can also be measured in this test. Two most common examples of these tests are a steering harmonic sweep test, in which the steer input is a harmonic function but with a slowly increasing frequency and the pseudo-random test as described in the ISO 8726 proposal [11]. This test is usually performed within or close to the linear range of handling.

Impulse Steer Test

In this maneuver, a vehicle is driven straight at a specific speed when a sudden steer input is generated with prompt restoration to straight ahead. This test demonstrates transient response of a vehicle in response to a sudden disturbance. It can also be used to generate frequency domain characteristics using Fourier transform methods.

CRITERIA FOR SELECTION

Among the test maneuvers described, there are some that do not characterize vehicle handling at the limit and therefore are inadequate for our purposes. There remain, however, several tests, which reveal similar aspects of handling performance or may even have similar steer patterns. In order to reduce the number of maneuvers, it is necessary to specify the criteria for selection. The criteria used here are listed below. Many of them are similar to those used by NHTSA in selecting the dynamic rollover test.

- **Objectivity and repeatability.** The outcome should be independent of the personnel performing the test, as long as the test procedure is being followed. The results should be repeatable for the same vehicle, so that they can be reproduced.
- **Feasibility** (ability to perform). This category describes how easy/difficult (or expensive) it is to perform the test. For example: is it time-consuming, does it require expensive instrumentation, special test track facility, a lot of effort (e.g. many iterations), etc.
- **Completeness** (handling metric measurement capability). This category describes how many aspects of vehicle handling performance can be evaluated in one test and how many metrics that quantify vehicle handling can be determined from the test data. The most important aspects

of handling are those that affect safety, as listed in the previous section.

- **Realistic character of the test.** This is an evaluation of whether the test has field relevance. That is whether or not it is similar to maneuvers performed by actual drivers, especially in emergency situations. Similarities to standard tests proposed by SAE, ISO or frequently used by automakers may also be taken into account.
- **Discriminatory capability.** Describes how effective the test is in capturing significant differences in vehicle handling qualities. It is not desirable to have the metrics derived from the tests performed on different vehicles to be clustered in the narrow range of values, especially when the differences are close to measurement errors.

Note that conflicts among the above criteria may exist. For example, requirements of objectivity and repeatability, implies that the results should be robust with respect to very small changes in parameters of vehicle, chassis or tires. This is somewhat in conflict with the requirement of discriminatory capability.

Using the above selection criteria, all types of maneuvers were ranked and the top three receiving the highest scores were selected for further development. They are as follows:

- Slowly increasing steer (skid pad) test
- Step steer test
- Open loop steer reversal test.

All selected maneuvers are open loop, in which a steering input can be performed by a robot. This provides a significant advantage over closed loop maneuvers in the area of objectivity and repeatability, but also in discriminatory capability, because human drivers can compensate for handling differences. The slowly increasing steer test reveals steady state handling characteristic and provides reference points for other tests, as will be discussed later. The step steer test provides both transient and steady state characteristics. The open loop steer reversal test is generally more demanding than the step steer test because vehicles are more prone to become unstable and spin out in this test. The steering pattern can resemble those experienced during emergency single and double lane changes.

DESCRIPTION OF SELECTED HANDLING TEST MANEUVERS

The selected maneuvers were further studied through vehicle testing and simulations using a validated model of a vehicle. The purpose was to determine the exact steering patterns, including steer rates and amplitudes, and entry speeds.

Slowly Increasing Steer Test

This test is well defined and is currently performed by NHTSA as part of dynamic rollover test procedure [2]. The maneuver is performed with a constant speed of 50 mph with steering angle ramping up at a rate of 15 degrees per second or less (NHTSA uses 13.5 deg/s). Since our goal is to reach the friction limit for some time in this test, the steering angle is increased up to 360 degrees or to the angle corresponding to the wheel lock position, whichever is smaller. The steering pattern is illustrated in Figure 4.

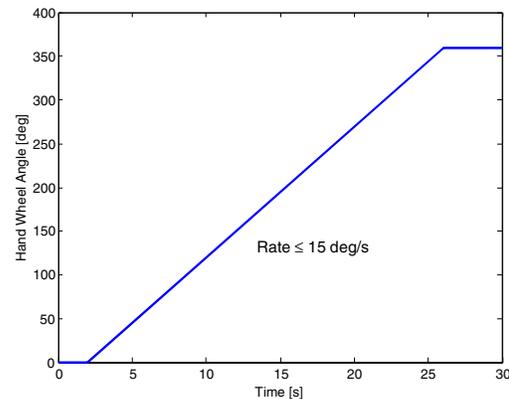


Figure 4. Steering pattern in slowly increasing steer test.

In addition to characterizing steady state response of the vehicle, this test provides characteristic values for the other tests and for determining performance goals in transient tests. For example, the steering angle amplitudes in the transient tests are the multiples of the steering angle corresponding to 0.3 g of lateral acceleration in this test.

Step Steer Test

In this test, the general steer pattern is well defined. In order to determine the entry speed, steering angle amplitude and rate of change during transient, series of simulations and vehicle testing were performed. In simulations, vehicle speed varied

from 35 to 90 mph, the steering angle amplitude from 30 to 360 degrees and steering rate from 500 deg/s to 2000 deg/s. The purpose was to determine the values that make the maneuver severe enough to reveal potential weakness in emergency handling, yet still appear realistic. It was found that vehicle response deteriorated with increasing speed, primarily by becoming more oscillatory, but safe speed for testing was found to be about 60 mph. Vehicle response also deteriorated with increasing steering angle, but only up to a certain value of the steering angle (which depended on speed). Vehicle response did not change significantly when the steer rate increased from 1000 to 2000 degrees per second. Consequently, the following parameters were selected for the step steer test:

- speed of entry 55 mph
- amplitude of steer angle 5 times the steering angle corresponding to 0.3 g of lateral acceleration in the slowly increasing steer test
- steer rate of 1000 degrees/second
-

The steering pattern is illustrated in Figure 5. The driver does not apply the throttle during the maneuver.

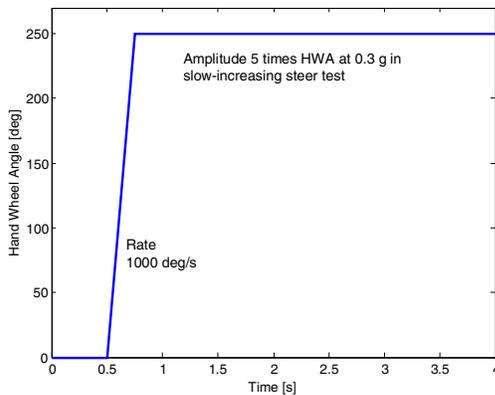


Figure 5. Steering pattern in step steer test.

Steer Reversal Test

The maneuvers with steer reversals considered here are the open loop pseudo lane change and open loop pseudo double lane change. These maneuvers, when performed at the limit, can be very challenging, in particular when reversals of steering angle are quick. When the steering angle of the front wheels is suddenly reversed, the front tire slip angles and consequently the front tire lateral forces are reversed,

while the rear axle lateral force lags, maintaining the direction supporting the first turn. As a result, the vehicle is, for some time, subjected to a pair of opposite lateral forces, which creates a large yaw moment causing a rapid rotation of the vehicle. This generally yields large overshoot in yaw rate and the development of a significant sideslip angle. In this type of maneuver, the timing of steering reversal(s) and the rate of change of steering angle have a very important influence on vehicle performance.

Several choices had to be made in developing the steering pattern for this test based on a validated simulation model for the test vehicle. First, a trapezoidal pattern was selected in favor of rounded one. While rounded, e.g. harmonic, pattern resembles the actual driver steering in emergency situations more closely, it poses difficulties in proper timing of steer reversal and generally provides less severe excitation of vehicle yaw motion than the trapezoidal steering of the same amplitude. Second, the steer pattern with two reversals, rather than one, was selected because it includes the latter, was found to provide more severe excitation and is in fact more akin to the steering patterns in emergency lane changes. Third, the time of initiation of each steering reversal was chosen to coincide with the peaks of vehicle yaw rate. This selection was found to provide the worst, or very close to the worst, response of vehicle in terms of stability. This timing is chosen to match the natural yaw response of vehicle, unlike in the fixed steering pattern, which could be criticized on the grounds that it may excite yaw modes of some vehicles more than others. The steering amplitude and rate were selected at the level observed in emergency lane changes performed by a human driver at the same speed. The chosen steering pattern is illustrated in Figure 6.

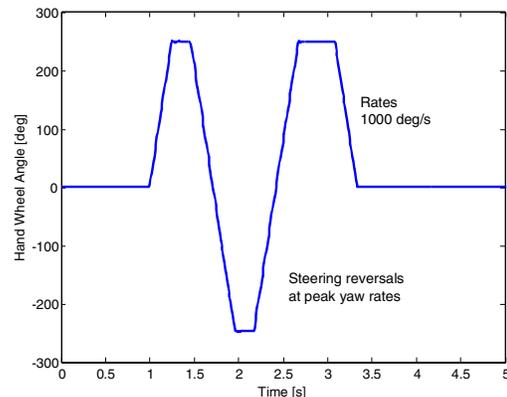


Figure 6. Steering pattern in steer reversal test.

The entry speed for this maneuver is 55 mph, the amplitude of steer angle is 5 times the steering angle corresponding to 0.3 g of lateral acceleration in the slowly increasing steer test, and all steer rates are 1000 deg/s. Note that the dwell time of the steering angle increases significantly in the last phase of maneuver as the lag in yaw response of vehicle to the steering input increases. No throttle is applied during this maneuver.

HANDLING METRICS

Vehicle design involves many compromises from the point of view of desired handling properties. The main trade off is between vehicle responsiveness to steering input and stability or predictability. In addition, large stability margin in steady state conditions, as expressed by understeer gradient, may compromise cornering ability (since front tires saturate well before the rear axle reaches the limit lateral force) and may lead to oscillatory response at high speeds, since the damping ratio of the roll mode decreases as speed increases at a rate proportional to understeer gradient [12]. In this section, a composite metric of vehicle performance is discussed. It should balance measures of several aspects of handling, which affect safety, as discussed earlier, and should include those aspects, which are difficult to reconcile.

Vehicle handling is usually evaluated in terms of vehicle response in the yaw plane as characterized by lateral acceleration, yaw rate and sideslip angle. It is known [13], however, that in the closed loop task performance tests the roll motion of vehicle, including both roll angle and roll rate, has a very significant effect on overall subjective rankings of vehicle handling. The main reason is that the driver steering control input, that is necessary to perform a difficult handling task (e.g. a quick lane change simulating an evasive maneuver), may be compromised if the vehicle exhibits substantial and poorly damped roll responses to rapid steering inputs. The secondary reason is that a driver continuously uses preview information about the path of travel to determine the necessary steer input for a given task. Changes in vehicle attitude, such as excessive roll motion, make this task more complicated. Thus, excessive and underdamped roll responses to rapid steering inputs should be penalized in the handling metric.

It is noted that several essentially identical performance measures can be used to describe different handling qualities influencing safety. This is because there is some overlap in the defined handling categories (for example, stability is necessary for predictability), but also there exists correlations among various metrics (for example, time delays tend to increase as tire sideslip angles increase). The following measures of performance are proposed to quantify various aspects of handling:

1. Measure of maximum lateral acceleration and quickness of achieving it.
2. Measure of oscillations in yaw response in transient maneuvers (yaw response overshoot in step steer, amplitude ratio(s) of yaw response in steer reversal test).
3. Measure of time delays in vehicle lateral response (time delays between steer angle and yaw rate and lateral acceleration in transient maneuvers, time delays between yaw rate and lateral acceleration in transient maneuvers).
4. Measure of lateral stability as expressed by rear axle slip angles (maximum slip angles or slip rates).
5. Measure of roll angle response (peak roll angle in step steer and steer reversal tests, peak roll rate, roll gain, roll angle overshoot in step steer test)

The rear axle slip angle was selected as a measure of vehicle stability, rather than the vehicle slip angle, since it is a more direct indicator of tire slip at all speeds and is less dependent on vehicle dimensions. Each of the above performance measures can be quantified, and a composite index can be constructed, which is a weighted sum of all components.

TEST RESULTS

In this section, selected results of vehicle testing are presented for two transient handling tests: step steer maneuver and the open loop double lane change test.

Step Steer Maneuver

Step steer maneuvers were performed multiple times for four different vehicle configurations: passive vehicle, vehicle with ESC system enabled, vehicle with ARS system enabled and vehicle with both ESC and ARS systems enabled. In this maneuver, the ESC system did not become active,

primarily because the passive vehicle was stable and well controlled in this test. Therefore, the results with ESC system enabled are the same as with the system turned off and are not shown here.

The results obtained in a right turn for a passive vehicle (test 09) and a vehicle with ARS on (test 19) are illustrated in Figure 7. In both cases, the initial speed was nearly identical. However, the vehicle with ARS system enabled maintains a higher speed throughout the maneuver because of reduced losses of energy due to tire sideslip. The rear wheel steer angle depends on the hand wheel angle and vehicle speed and is initially of the same sign as the front steering angle, then of the opposite sign, with the sign change occurring at about 40 mph (65 km/h). The magnitude of the rear wheel steering angle does not exceed 3 degrees in the recorded portion of maneuver, yet the effects are quite dramatic. In particular, the overshoots in yaw rate and rear tire slip angles are almost entirely eliminated.

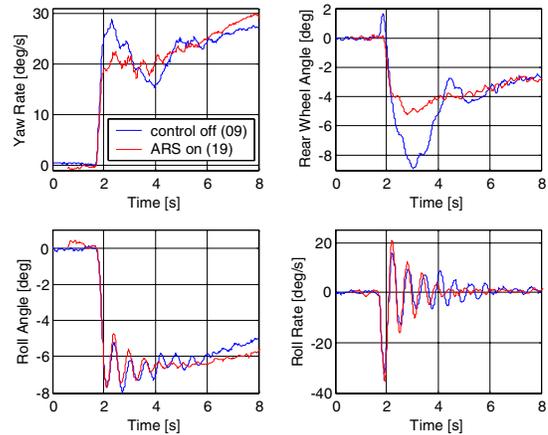
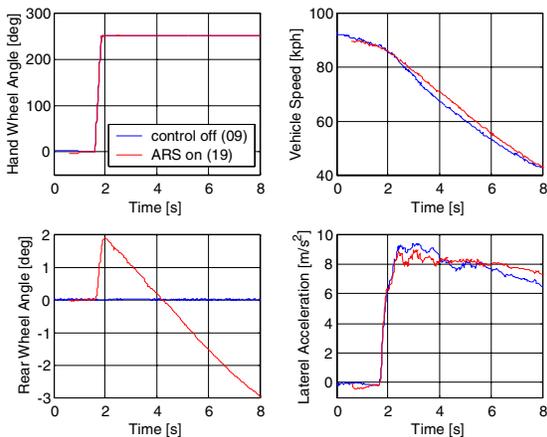


Figure 7. Comparison of vehicle responses in open loop step steer maneuver for passive vehicle and vehicle with ARS system enabled.

The peak value of rear tire slip angle is reduced from 8.9 to 5.2 degrees (a reduction of over 40%) and the first peak in yaw rate is suppressed from about 28.8 to 22.5 degrees/second. Lateral acceleration response is reduced by about 0.5 m/s^2 in the first two seconds of maneuver, as compared to the passive vehicle. The peak roll angles are about the same in both cases, but the peak roll rate is slightly higher in the case of the vehicle with the ARS system enabled. This is most likely due to slightly faster initial lateral acceleration response. The roll response, however, is better damped when the ARS system is enabled, primarily because of slightly lower lateral acceleration at the limit. Overall, the changes in roll response brought about by the ARS system were very small.



This example test result highlights the importance of having a composite index of handling that balances all the important, but often conflicting, aspects of performance. The ARS system significantly improves yaw response in terms of both speed of response and stability, but it reduces maximum lateral acceleration slightly.

Open Loop Double Lane Change

Open loop double lane change maneuvers were performed with passive vehicle and vehicle with ESC system enabled. In Figure 8, the importance of appropriate timing of steer reversals in this maneuver is illustrated. Here the results obtained in two open loop double lane change maneuvers for a passive

vehicle are shown. Both were performed at the same entry speed, with the only difference being the dwell times in the last steering input, which were 0.3 second and 0.4 seconds, respectively. In the former case, the last steer angle reversal occurred before the yaw rate reached maximum value; while in the latter the steer reversal coincided with the peak yaw rate. Since after about 5.5 seconds the driver provided a very large steering correction in the second case, the traces beyond this time should be disregarded. The differences in vehicle responses are quite dramatic, with the vehicle reaching much higher peak values of rear axle sideslip angle, lateral acceleration, roll angle and slightly higher yaw rate in the maneuver, in which the last steer reversal coincides with peak yaw rate (dotted line).

In Figure 9, vehicle responses in open loop double lane changes are compared with the ESC system on (test 22) and off (test 19). The ESC system is activated shortly after the first steering reversal, as shown by the red line in the left top plot box. The system has a small effect on the second peaks in yaw rate, lateral acceleration and rear axle slip angle. In the final phase of the maneuver, however, the peak values of all three variables are reduced. The most pronounced effect is observed in rear axle slip angle response. For example, the peak value is reduced from 19.1 degrees for passive system to 13.8 degrees for vehicle with the system on. Delays in vehicle lateral acceleration and yaw rate responses are also significantly reduced in the last phase of the maneuver, making vehicle response more predictable. It should be noted that the ESC system used in the tests described here was operating in a less aggressive mode, tuned for non-obtrusive operation and referred to as configuration 1 in the second section. At the completion of the maneuver, the differences in vehicle speed between the tests with system on and off are only about 4 km/h, indicating relatively mild brake interventions. Note that the ESC system tuned in this manner improves significantly several aspects of handling performance without significant trade off.

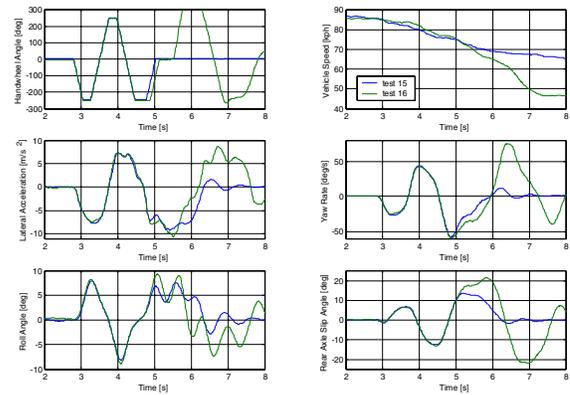


Figure 8. Vehicle responses in two open loop double lane change maneuvers performed with different timing of last steer reversal.

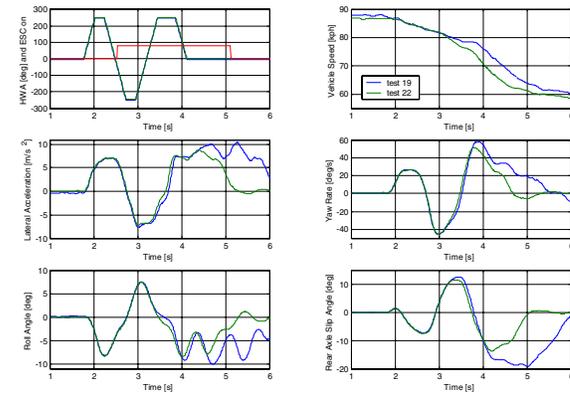


Figure 9. Vehicle responses in two open loop double lane change maneuvers performed with ESC system on (test 22) and off (test 19).

CONCLUSIONS

In this paper, a process used for development of an objective and repeatable test procedure to evaluate vehicle handling is described. Three open-loop handling tests are proposed, which may be used to evaluate the aspects of handling which influence safety. These tests, along with the dynamic rollover test proposed by NHTSA, are used to evaluate the effects of two active chassis systems on handling and rollover stability. The active chassis systems used are ESC and ARS systems. The following conclusions can be derived from this study: 1) tuning of ESC system can have a significant effect on

vehicle roll response in the dynamic rollover test; 2) for some vehicles, a step steer test as described in this paper may not be severe enough to activate the ESC system; if showing the effect of ESC is a desired goal, an alternative test may be considered; 3) the ARS system can significantly improve most aspects of vehicle handling performance in the step steer test; 4) the open loop double lane change test is more demanding than the step steer test or an open loop single lane change test performed at the same speed and steering angle; 5) timing of steering reversals is very important in the open loop double lane change; for the vehicle tested here, the initiation of reversals, which coincided with peak yaw rates, rendered the least stable yaw response of vehicle; 6) an ESC system can significantly improve vehicle yaw stability and responsiveness in the second phase of the open loop steer reversal test, without adversely affecting other aspects of handling performance.

REFERENCES

1. NHTSA DOT HS DOT HS 809 775, 2005, "Traffic Safety Facts 2003 FARS/GES Annual Report (Final Edition)", National Highway Traffic Safety Administration, Washington, D.C.
2. NHTSA DOT HS 809 513, 2002, "A Comprehensive Experimental Evaluation of Test maneuvers That May Induce On-Road, Untripped, Light Vehicle Rollover. Phase IV of NHTSA's Light Vehicle Rollover Research Program," National Highway Traffic Safety Administration, Washington, D.C.
3. NHTSA Report, 2004, "Advanced Occupant Protection Technology in Passenger Vehicles. Influence of Active Chassis Systems on Vehicle Dynamic Stability and Handling," National Highway Traffic Safety Administration, Washington, D.C.
4. Consumer Reports, 2003, New Car Preview 2004, December 2003.
5. SAE Standard J266.
6. International Standard ISO 4138, 1996, "Road Vehicles – Steady State Circular Test Procedure".
7. International Standard ISO 7401, 1997, "Road Vehicles – Lateral Transient Response Test Methods".
8. International Standard ISO 7975, "Braking in Turn – Open Loop Test Procedure".
9. International Standard ISO/TR 8725, 1988, "Road Vehicles – Transient Open-Loop Response Test Method with One Period of Sinusoidal Input".
10. International Standard ISO/DIS 3888, 1997, "Passenger Cars – Test Track for a Severe Lane-Change Maneuver".
11. International Standard ISO/TR 8726, 1988, "Road Vehicles – Transient Open-Loop Response Test Method with Pseudo-Random Input.
12. Dixon, J. C., 1996, "Tires, Suspension and Handling", 2nd edition, SAE Inc., Warrendale, PA.
13. Data, S. C. and Frigerio, F., 2002, "Objective Evaluation of Handling Quality", Proceedings of Institution of Mechanical Engineers, Part D Journal of Automobile Engineering, Vol. 21.

NHTSA'S NCAP ROLLOVER RESISTANCE RATING SYSTEM

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ABSTRACT

Starting in the 2004 model year, the National Highway Traffic Safety Administration (NHTSA) improved the rollover resistance ratings in its New Car Assessment Program (NCAP) consumer information by adding a dynamic maneuver test. NHTSA had provided rollover resistance ratings in the 2001 – 2003 model years based solely on the Static Stability Factor (SSF) measurement of vehicles. The ratings express the risk of a vehicle rolling over in the event of a single vehicle crash, the type of crash in which most rollovers occur. The SSF, which is determined by a vehicle's center of gravity height and track width, had proved to be a powerful predictor of rollover risk based on a linear regression study of rollover rates of 100 vehicle models in 224,000 single vehicle crashes ($R^2 = 0.88$).

The TREAD Act required NHTSA to change its rollover resistance ratings to use a dynamic maneuver test, and the 2004 and later NCAP rollover resistance ratings use both SSF and a dynamic maneuver. This paper describes the development of the risk prediction model used for present rating system. Twenty-five vehicles were tested using two highly objective automated steering maneuvers (J-turn and Fishhook) at two levels of passenger loading. A logistic regression risk model was developed based on the rollover outcomes of 86,000 single-vehicle crashes involving the make/models that were tested. The vehicles were characterized by their SSF measurements and binary variables indicating whether or not they had tipped up during the maneuver tests. It was found that the Fishhook test in the heavy (5 passenger equivalent) load was the most useful maneuver test for predicting rollover risk. The relative predictive powers of the SSF measurement and the Fishhook test were established by a logistic regression model operating on the rollover outcomes of real-world crash data. This model was used to predict the rollover rates of vehicles in the 2004 and 2005 NCAP program based on their SSF measurements and Fishhook maneuver test performance. The information in this paper first appeared in NHTSA's Federal Register notice [1] that established the NCAP rollover resistance rating system for model year 2004.

INTRODUCTION

Prior NCAP Program and the TREAD Act

NHTSA's NCAP program has been publishing comparative consumer information on frontal crashworthiness of new vehicles since 1979, on side crashworthiness since 1997, and on rollover resistance since January 2001.

The 2001-2003 NCAP rollover resistance ratings were based on the Static Stability Factor (SSF) of a vehicle, which is the ratio of one half its track width to its center of gravity (C.G.) height. After an evaluation of some driving maneuver tests in 1997 and 1998, NHTSA chose to use SSF instead of any driving maneuvers to characterize rollover resistance. NHTSA chose SSF as the basis of NCAP ratings because it represents the first order factors that determine vehicle rollover resistance in the vast majority of rollovers which are tripped by impacts with curbs, soft soil, pot holes, guard rails, etc. or by wheel rims digging into the pavement. In contrast, untripped rollovers are those in which tire/road interface friction is the only external force acting on a vehicle that rolls over. Driving maneuver tests directly represent on-road untripped rollover crashes, but such crashes represent less than five percent of rollover crashes [2].

At the time, NHTSA believed it was necessary to choose between SSF and driving maneuver tests as the basis for rollover resistance ratings. SSF was chosen because it had a number of advantages: it is highly correlated with actual crash statistics; it can be measured accurately and inexpensively and explained to consumers; and changes in vehicle design to improve SSF are unlikely to degrade other safety attributes. NHTSA also considered the fact that an improvement in SSF represents an increase in rollover resistance in both tripped and untripped circumstances while maneuver test performance can be improved by reduced tire traction and certain implementations of electronic stability control that it believes are much less likely than SSF improvements to increase resistance to tripped rollovers.

Congress directed the agency to enhance the NCAP rollover resistance rating program. Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000" directs the Secretary to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests. As the Secretary develops a [rollover] test, the Secretary shall conduct a rulemaking to determine how best to disseminate test results to the public." The rulemaking was to be carried out by November 1, 2002.

Research and Public Comment on Dynamic Rollover Tests

On July 3, 2001, NHTSA published a Request for Comments notice (66 FR 35179) regarding its research plans to assess a number of possible dynamic rollover tests. The notice discussed the possible advantages and disadvantages of various approaches that had been suggested by manufacturers, consumer groups, and NHTSA's prior research. The driving maneuver tests to be evaluated fit into two broad categories: closed-loop maneuvers in which all test vehicles attempt to follow the same path, and open-loop maneuvers in which all test vehicles are given equivalent steering inputs. The principal theme of the comments was a sharp division of opinion about whether the dynamic rollover test should be a closed loop maneuver test like the ISO 3888 double lane change that emphasizes the handling properties of vehicles or whether it should be an open loop maneuver like a J-Turn or Fishhook that are limit maneuvers in which vulnerable vehicles would actually tip up. Ford recommended a different type of closed loop lane change maneuver in which a path-following robot or a mathematical correction method would be used to evaluate all vehicles on the same set of paths at the same lateral acceleration. It used a measurement of partial wheel unloading without tip-up at 0.7g lateral acceleration as a performance criterion in contrast to the other closed loop maneuver tests that used maximum speed through the maneuver as the performance criterion. Another unique comment was a recommendation from Suzuki to use a sled test developed by Exponent Inc. to simulate tripped rollovers.

The subsequent test program [3] (using four SUVs in various load conditions and with and without electronic stability control enabled on two of the SUVs) showed that open-loop maneuver tests using an automated steering controller could be performed with better repeatability of results than the other maneuver tests. The J-Turn maneuver and the

Fishhook maneuver (with steering reversal at maximum vehicle roll angle) were found to be the most objective tests of the susceptibility of vehicles to maneuver-induced on-road rollover. Except for the Ford test, the closed loop tests were found not to measure rollover resistance. Instead, the evaluation criterion of maximum maneuver entrance speed measured just prior to entering a double lane change assessed vehicle agility. None of the test vehicles tipped up during runs in which they maintained the prescribed path even when loaded with roof ballast to experimentally reduce their rollover resistance. The speed scores of the test vehicles in the closed loop maneuvers were found to be unrelated to their resistance to tip-up in the open-loop maneuvers that actually caused tip-up. The test vehicle that was clearly the poorest performer in the maneuvers that caused tip-ups achieved the best score (highest speed) in the ISO 3888 and CU short course double lane change, and one vehicle improved its score in the ISO 3888 test when roof ballast was added to reduce its rollover resistance.

Due to the non-limit test conditions and the averaging necessary for stable wheel force measurements, the wheel unloading measured in the Ford test appeared to be more quasi-static (as in driving in a circle at a steady speed or placing the vehicle on a centrifuge) than dynamic. Sled tests were not evaluated because NHTSA believed that SSF already provided a good indicator of resistance to tripped rollover.

National Academy of Sciences Study

During the time NHTSA was evaluating dynamic maneuver tests in response the TREAD Act, the National Academy of Sciences (NAS) was conducting a study of the SSF-based rollover resistance ratings and was directed to make recommendations regarding driving maneuver tests. NHTSA expected the NAS recommendations to have a strong influence on TREAD-mandated changes to NCAP rollover resistance ratings.

When NHTSA proposed the prior (SSF only) rollover resistance ratings in June 2000, vehicle manufacturers generally opposed it because they believed that SSF as a measure of rollover resistance is too simple since it does not include the effects of suspension deflections, tire traction and electronic stability control (ESC). In addition, the vehicle manufacturers argued that the influence of vehicle factors on rollover risk is too slight to warrant consumer information ratings for rollover resistance. In the conference report of the FY2001 DOT Appropriations Act, Congress permitted NHTSA to

move forward with its rollover rating program, but directed the agency to fund a National Academy of Sciences (NAS) study on vehicle rollover ratings. The study topics were “whether the static stability factor is a scientifically valid measurement that presents practical, useful information to the public including a comparison of the static stability factor test versus a test with rollover metrics based on dynamic driving conditions that may induce rollover events.” The National Academy’s report was completed and made available at the end of February 2002 [4].

The NAS study found that SSF is a scientifically valid measure of rollover resistance for which the underlying physics and real-world crash data are consistent with the conclusion that an increase in SSF reduces the likelihood of rollover. It also found that dynamic tests should complement static measures, such as SSF, rather than replace them in consumer information on rollover resistance. The dynamic tests the NAS recommended would be driving maneuvers used to assess “transient vehicle behavior leading to rollover.”

The NAS study also made recommendations concerning the statistical analysis of rollover risk and the representation of ratings. It recommended that NHTSA use logistic regression rather than linear regression for analysis of the relationship between rollover risk and SSF, and it recommended that NHTSA consider a higher-resolution representation of the relationship between rollover risk and SSF than is provided by a five-star rating system.

NHTSA published a Federal Register notice on October 7, 2002 (67 FR 62528) that proposed to modify the NCAP rollover resistance ratings to satisfy the requirements of the TREAD Act and to align it with the recommendation of the NAS report. NHTSA chose the J-Turn and Fishhook maneuver (with roll rate feedback) as the dynamic maneuver tests because they were the type of limit maneuver tests that could directly lead to rollover as recommended by the NAS. NHTSA also proposed to use a logistic regression analysis to determine the relationship between vehicle properties and rollover risk, as recommended by the NAS.

DYNAMIC MANEUVER TESTS OF 25 VEHICLES

The original NCAP rollover resistance ratings predicted the rate of rollovers per single vehicle crash based on the SSF of vehicles. Stars were used to express rollover risk in rate increments of 10% (i.e., 2

stars for a predicted rollover rate between 30 and 40%, 3 stars for a predicted rollover rate between 20 and 30%, etc.). The relationship between rollover rate and SSF was determined using a linear regression between the logarithm of SSF and the actual rollover rates of 100 vehicle make/models [5]. The rollover rates were determined from 224,000 state crash reports and were corrected for differences between vehicles in demographic and road condition variables reported by the states.

The idea for improving the prediction of rollover rate (the risk model) using dynamic maneuver tests was to describe the vehicle by its SSF plus a number of variables resulting from the vehicle’s behavior in the dynamic maneuvers. In that way, the risk model would consider more than just the geometric properties of the vehicle. Four binary variables were anticipated. They would describe whether the vehicle tipped up or did not in the J-turn and in the Fishhook maneuver, each performed with the vehicle in two passenger load configurations. The risk model for predicting rollover rate on the basis of SSF plus dynamic test results would be determined using logistic regression between the rollover outcomes of state crash reports of single vehicle crashes of a number of vehicles and the new set of vehicle attributes (SSF plus dynamic test variables). The expression of rollover risk by stars would continue with the same relationship between the number of stars and the predicted rollover rate.

The linear regression, SSF only, risk model used crash data on 100 vehicles, but it was impractical to perform maneuver tests on that many vehicles to develop the present risk model. This section presents an overview of the test maneuvers and the results for the subset of 25 vehicles selected for developing the logistic regression risk model. A more extensive account of the test program is contained in the Phase VI and VII rollover research report [6]. The NHTSA J-Turn and Fishhook (with roll rate feedback) maneuver tests were performed for 25 vehicles representing four vehicle types including passenger cars, vans, pickup trucks and SUVs. NHTSA chose mainly high production vehicles that spanned a wide range of SSF values, using vehicles NHTSA already owned where possible. Except for four 2001 model year vehicles NHTSA purchased new, the vehicle suspensions were rebuilt with new springs and shock absorbers, and other parts as required for all the other vehicles included in the test program.

J-Turn Maneuver

The NHTSA J-Turn maneuver represents an

avoidance maneuver in which a vehicle is steered away from an obstacle using a single input. The maneuver is similar to the J-Turn used during NHTSA's 1997-98 rollover research program and is a common maneuver in test programs conducted by vehicle manufacturers and others. Often the J-Turn is conducted with a fixed steering input (handwheel angle) for all test vehicles. In its 1997-98 testing, NHTSA used a fixed handwheel angle of 330 degrees. During the development of the present tests, NHTSA developed an objective method of specifying equivalent handwheel angles for J-Turn tests of various vehicles, taking into account their differences in steering ratio, wheelbase and linear range understeer properties [3]. Under this method, one first measures the handwheel angle that would produce a steady-state lateral acceleration of 0.3 g at 50 mph on a level paved surface for a particular vehicle. In brief, the 0.3 g value was chosen because the steering angle variability associated with this lateral acceleration is quite low and there is no possibility that stability control intervention could confound the test results. Since the magnitude of the handwheel position at 0.3 g is small, it must be multiplied by a scalar to have a high maneuver severity. In the case of the J-Turn, the handwheel angle at 0.3 g was multiplied by eight. When this scalar is multiplied by handwheel angles commonly observed at 0.3 g, the result is approximately 330 degrees. Figure 1 illustrates the J-Turn maneuver in terms of the automated steering inputs commanded by the programmable steering machine. The rate of the handwheel turning is 1000 degrees per second.

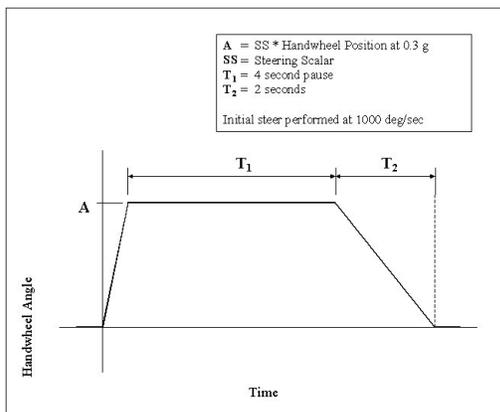


Figure 1. NHTSA J-turn maneuver description.

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, coasted to the target speed, and then triggered the commanded handwheel input. The

nominal maneuver entrance speeds used in the J-Turn maneuver ranged from 35 to 60 mph, increased in 5 mph increments until a termination condition was achieved. Termination conditions were simultaneous two inch or greater lift of a vehicle's inside tires (two-wheel lift) or completion of a test performed at the maximum maneuver entrance speed without two-wheel lift. If two-wheel lift was observed, a downward iteration of vehicle speed was used in 1 mph increments until such lift was no longer detected. Once the lowest speed for which two-wheel lift could be detected was isolated, two additional tests were performed at that speed to monitor two-wheel lift repeatability.

Fishhook Maneuver

The Fishhook maneuver uses steering inputs that approximate the steering a driver acting in panic might use in an effort to regain lane position after dropping two wheels off the roadway onto the shoulder. NHTSA has often described it as a road edge recovery maneuver. As pointed out by some commenters, it is performed on a smooth pavement rather than at a road edge drop-off, but its rapid steering input followed by an over-correction is representative of a general loss of control situation. The original version of this test was developed by Toyota, and variations of it were suggested by Nissan and Honda. NHTSA has experimented with several versions since 1997, and the present test includes roll rate feedback in order to time the counter-steer to coincide with the maximum roll angle of each vehicle in response to the first steer.

Figure 2 describes the Fishhook maneuver in terms of the automated steering inputs commanded by the programmable steering machine and illustrates the roll rate feedback. The initial steering magnitude and countersteer magnitudes are symmetric, and are calculated by multiplying the handwheel angle that would produce a steady state lateral acceleration of 0.3 g at 50 mph on level pavement by 6.5. When this scalar is multiplied by handwheel angles commonly observed at 0.3 g, the result is approximately 270 degrees. This is equivalent to the 270 degree handwheel angle used in earlier forms of the maneuver but, as in the case of the J-Turn, the procedure above is an objective way of compensating for differences in steering gear ratio, wheelbase and understeer properties between vehicles. The fishhook maneuver dwell times (the time between completion of the initial steering ramp and the initiation of the countersteer) are defined by the roll motion of the vehicle being evaluated, and can vary on a test-to-test basis. This is made possible by having the steering

machine monitor roll rate (roll velocity). If an initial steer is to the left, the steering reversal following completion of the first handwheel ramp occurs when the roll rate of the vehicle first equals or goes below 1.5 degrees per second. If an initial steer is to the right, the steering reversal following completion of the first handwheel ramp occurs when the roll rate of the vehicle first equals or exceeds -1.5 degrees per second. The handwheel rates of the initial steer and countersteer ramps are 720 degrees per second.

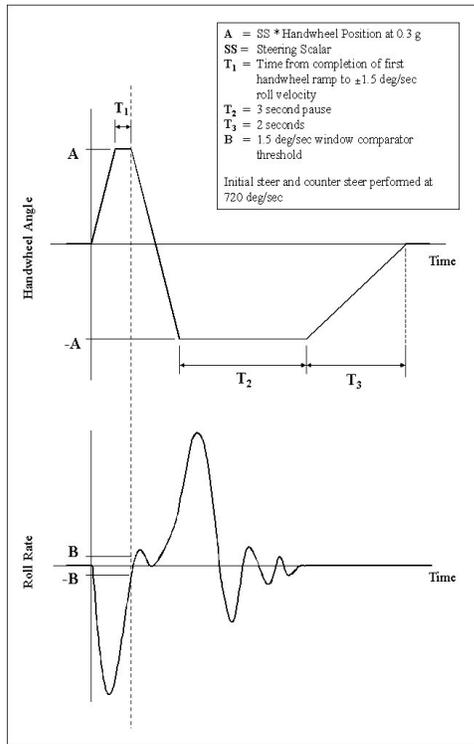


Figure 2. NHTSA Fishhook maneuver description.

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, coasted to the target speed, and then triggered the commanded handwheel input described in Figure 2. The nominal maneuver entrance speeds used in the fishhook maneuver ranged from 35 to 50 mph, increased in 5 mph increments until a termination condition was achieved. Termination conditions included simultaneous two inch or greater lift of a vehicle’s inside tires (two-wheel lift) or completion of a test performed at the maximum maneuver entrance speed without two-wheel lift. If two-wheel lift was observed, a downward iteration of vehicle speed was used in 1 mph increments until

such lift was no longer detected. Once the lowest speed for which two-wheel lift could be detected was isolated, two additional tests were performed at that speed to check two-wheel lift repeatability.

NHTSA observed that during the Fishhook tests, excessive steering caused some vehicles to reach their maximum roll angle response to the initial steering input before it had been fully completed (this is essentially equivalent to a “negative” T_1 in Figure 2). Since dwell time duration can have a significant effect on how the Fishhook maneuver’s ability to produce two-wheel lift, excessive steering may stifle the most severe timing of the counter steer for some vehicles. In an attempt to better insure high maneuver severity, a number of vehicles that did not produce two-wheel lift with steering inputs calculated with the 6.5 multiplier were also tested with lesser steering angles by reducing the multiplier to 5.5. This change increased the dwell times observed during the respective maneuvers. Some vehicles tipped up in Fishhook maneuvers conducted at the lower steering angle (5.5 multiplier) but not at the higher steering angle (6.5 multiplier). NHTSA adopted the practice of performing Fishhook maneuvers at both steering angles for NCAP.

Loading Conditions

The vehicles were tested in each maneuver in two load conditions in order to create four levels of stringency in the suite of maneuver tests. The light load was the test driver plus instrumentation in the front passenger seat, which represented two occupants. A heavier load was used to create a higher level of stringency for each test. In our NPRM, NHTSA announced that the heavy load would include 175 lb anthropomorphic forms (water dummies) in all rear seat positions. During the test of the 25 vehicles, it became obvious that heavy load tests were being run at very unequal load conditions especially between vans and other vehicles (two water dummies in some vehicles but six water dummies in others). While very heavy passenger loads can certainly reduce rollover resistance and potentially cause special problems, crashes at those loads are too few to greatly influence the overall rollover rate of vehicles. Over 94% of van rollovers in our 293,000 crash database occurred with five or fewer occupants, and over 99% of rollovers of other vehicles occurred with five or fewer occupants. The average passenger load of vehicles in our crash database was less than two: 1.81 for vans; 1.54 for SUVs; 1.48 for cars; and 1.35 for pickup trucks. In order to use the maneuver tests to predict real-world rollover rates, it seemed inappropriate to test the

vehicles under widely differing loads that did not correspond to the real-world crash statistics. Therefore, the tests used to develop a statistical model of rollover risk were changed to a uniform heavy load condition of three water dummies (representing a 5-occupant loading) for all vehicles capable of carrying at least five occupants. Some vehicles were loaded with only two water dummies because they were designed for four occupants. For pickup trucks, water dummies were loaded in the bed at approximately the same height as a passenger in the front seat.

Test Results

The test results in Table 1 (presented on the next page) reflect the performance as described for a heavy load condition representing five occupants except for the Ford Explorer 2DR, the Chevrolet Tracker and Metro that were designed for only four occupants, and the Honda CRV, Honda Civic and Chevrolet Cavalier that could not be loaded to the 5-occupant level without exceeding a gross axle weight rating because of the additional weight of the outriggers.

Each test vehicle in Table 1 represented a generation of vehicles whose model year range is given. Twenty-four of the vehicles were taken from 100 vehicle groups whose 1994-98 crash statistics in six states were the basis of the present SSF based rollover resistance ratings. The nominal SSFs used to describe the vehicle groups in the prior statistical studies are given. While there were some variations between the SSFs of the individual test vehicles and the nominal vehicle group SSF values, the nominal SSFs were retained for the present statistical analyses because they represent vehicles produced over a wide range of years in many cases and provide a simple comparison between the risk model presented in this notice and that discussed in the previous notices.

The X's under the various test maneuver names indicate which vehicles tipped up during the tests. Eleven of the twenty-five vehicles tipped up in the Fishhook maneuver conducted in the heavy condition. The heavy condition represented a five-occupant load for all vehicles except the six mentioned above that were limited to a four-occupant load by the vehicle seating positions and GVWR. All eleven were among the sixteen test vehicles with SSFs less than 1.20. None of the vehicles with higher SSFs tipped up in any test maneuver. The Fishhook test under the heavy load clearly had the greatest potential to cause tip-up. The groups of vehicles that tipped up in other tests were subsets of

the larger group of eleven that tipped up in the Fishhook Heavy test. There were seven vehicles in the group that tipped up in the J-Turn Heavy test, six of which also tipped up in the Fishhook Light test. The J-Turn Light test had the least potential to tip up vehicles. Only three vehicles tipped up, all of which had tipped up in every other test.

ROLLOVER RISK MODEL

In its study of NHTSA's rating system for rollover resistance [4], the National Academy of Sciences (NAS) recommended that NHTSA use logistic regression rather than linear regression for analysis of the relationship between rollover risk and SSF. Logistic regression has the advantage that it operates on every crash data point directly rather than requiring that the crash data be aggregated by vehicle and state into a smaller number of data points. For example, NHTSA now has state data reports of about 293,000 single-vehicle crashes of the hundred vehicle make/models (together with their corporate cousins) whose single-vehicle crashes NHTSA have been tracking in six states. The logistic regression analysis of this data would have a sample size of 293,000, producing a narrow confidence interval on the repeatability of the relationship between SSF and rollover rate. In contrast, the linear regression analysis operates on the rollover *rate* of the hundred vehicle make/models in each of the six states. It produces a maximum sample size of only 600 (100 vehicles times six states) minus the number of samples for which fewer than 25 crashes were available for determining the rollover rate (a data quality control practice). Confidence limits computed for a data sample size of 600 will be much greater than those based on a sample size of 293,000. On average, each sample in the linear regression analysis was computed from over 400 crash report samples. However, ordinary techniques to compute the confidence intervals of linear regression results do not take into account the actual sample size represented by aggregated data. The statistical model created to combine SSF and dynamic test information in the prediction of rollover risk was computed by means of logistic regression as recommended by the NAS. Logistic regression is well suited to the correlation with crash data of vehicle properties that include both continuous variables like SSF and binary variables like tip-up or no tip-up in maneuver tests.

NHTSA had previously considered logistic regression during the development of the SSF based rating system [4], but found that it consistently under-predicted the actual rollover rate at the low end of the

Table 1. Dynamic Maneuver Test Results (the X indicates tip-up observed).

Model Range, Make / Model	Nominal Static Stability Factor	Fishhook Light (FL) (2 occ.)	Fishhook Heavy (FH) (5 occ.)	J-Turn Light (JL) (2 occ.)	J-Turn Heavy (JH) (5 occ.)
'92 – '00 Mitsubishi Montero 4WD	0.95	X	X	--	X
'95 – '03 Chevrolet Blazer 2WD	1.02	X	X	--	X
'95 – '01 Ford Explorer 2dr 2WD	1.06	--	--	--	--
'95 – '01 Ford Explorer 4dr 4WD	1.06	--	X	--	--
'96 – '00 Toyota 4Runner 4WD	1.06	--	X	--	--
'93 – '97 Ford Ranger p/u 4WD	1.07	X	X	X	X
'88 – '97 Jeep Cherokee 4WD	1.08	--	--	--	--
'95 – '02 Acura SLX / Isuzu Trooper 4WD	1.09	X	X	X	X
'88 – '98 Ford Aerostar 2WD	1.10	X	X	X	X
'88 – '02 Chevrolet Astro 2WD	1.12	--	X	--	--
'89 – '98 Chevrolet/Geo Tracker 4WD	1.13	--	X	--	--
'88 – '98 Chevrolet K1500 p/u 4WD	1.14	--	--	--	--
'93 – '97 Ford Ranger p/u 2WD	1.17	--	X	--	X
'97 – '02 Ford F-150 p/u 2WD	1.18	--	--	--	--
'97 – '01 Honda CR-V 4WD	1.19	X	X	--	X
'88 – '96 Ford F-150 p/u 2WD	1.19	--	--	--	--
'88 – '95 Dodge Caravan / Plymouth Voyager 2WD	1.21	--	--	--	--
'88 – '98 Chevrolet C1500 p/u 2WD	1.22	--	--	--	--
'96 – '00 Dodge Caravan / Plymouth Voyager 2WD	1.23	--	--	--	--
'95 – '98 Ford Windstar 2WD	1.24	--	--	--	--
'95 – '01 Chevrolet / Geo Metro	1.29	--	--	--	--
'88 – '94 Chevrolet Cavalier	1.32	--	--	--	--
'91 – '96 Chevrolet Caprice	1.40	--	--	--	--
'88 – '95 Ford Taurus	1.45	--	--	--	--
'92 – '95 Honda Civic	1.48	--	--	--	--
Total Tip-ups		6	11	3	7

SSF range where the rollover rates are high. The NAS study acknowledged this situation and gave the example of another analysis technique (non-parametric) that made higher rollover rate predictions at the low end of the SSF scale. NHTSA decided to first examine ways to improve the fit of the logistic

regression model to the actual rollover rates in the simpler model with SSF as the only vehicle attribute before expanding the logistic regression model to predict rollover rates using maneuver test results and SSF as vehicle attributes. In this way, the addition of maneuver test results is more likely to have an effect

that reflects the additional information it represents on rollover causation.

Appendix II of reference [1] discusses the details of seeking a mathematical transformation of SSF to improve the accuracy of logistic regression models. NHTSA found that logistic regression on the transformation “ $\text{Log}(\text{SSF} - 0.9)$ ” rather than on SSF directly computed a risk model whose predictions of rollovers per single-vehicle crash more closely matched the relationship between vehicle SSF and actual rollover rates observed in state crash data. NHTSA sought to optimize the accuracy of the predictions in the SSF range between 1.0 and 1.25 that includes the vehicles with the highest rollover rates, even at the expense of accuracy in predicting the low rollover rates at high end of the SSF scale.

The risk model that resulted from this exercise is equivalent to the SSF-based rating system used for 2001-2003 NCAP rollover resistance ratings except that it was computed using logistic regression rather than linear regression as the statistical technique. Figure 3 compares the logistic regression model and linear regression model formerly used for NCAP ratings. The linear regression model is not in the form of a straight line because it also operated on a transformation of SSF ($\text{Log}(\text{SSF})$ in this case). The

logistic regression model is the more accurate at lower end of the SSF range, and the linear regression model is the more accurate at the upper end of the SSF range. But, the two curves are quite similar.

A good logistic regression risk model using SSF only was the starting point for models using dynamic variables together with SSF. The dynamic maneuver test results (tip-up or no tip-up in each maneuver/load combination in Table 1) were used as four binary dynamic variables in the logistic regression analysis. The dynamic variables were entered in addition to SSF to describe the vehicle. The same driver and road variables from state crash reports discussed above were used. The state crash report data for twenty four of the vehicles used in the logistic regression analysis with dynamic maneuver test variables was a subset of the database of 293,000 single-vehicle crashes described above. One extra vehicle was added for the maneuver tests that was not among the 100 vehicle groups NHTSA had studied previously, but state crash report data from the same years and states was obtained for it. However, the database with SSF and dynamic maneuver test results was much smaller than the 293,000 sample size available for the logistic regression model with SSF only. Its sample size was 96,000 single-vehicle crashes of 25 vehicles including 20,000 rollovers.

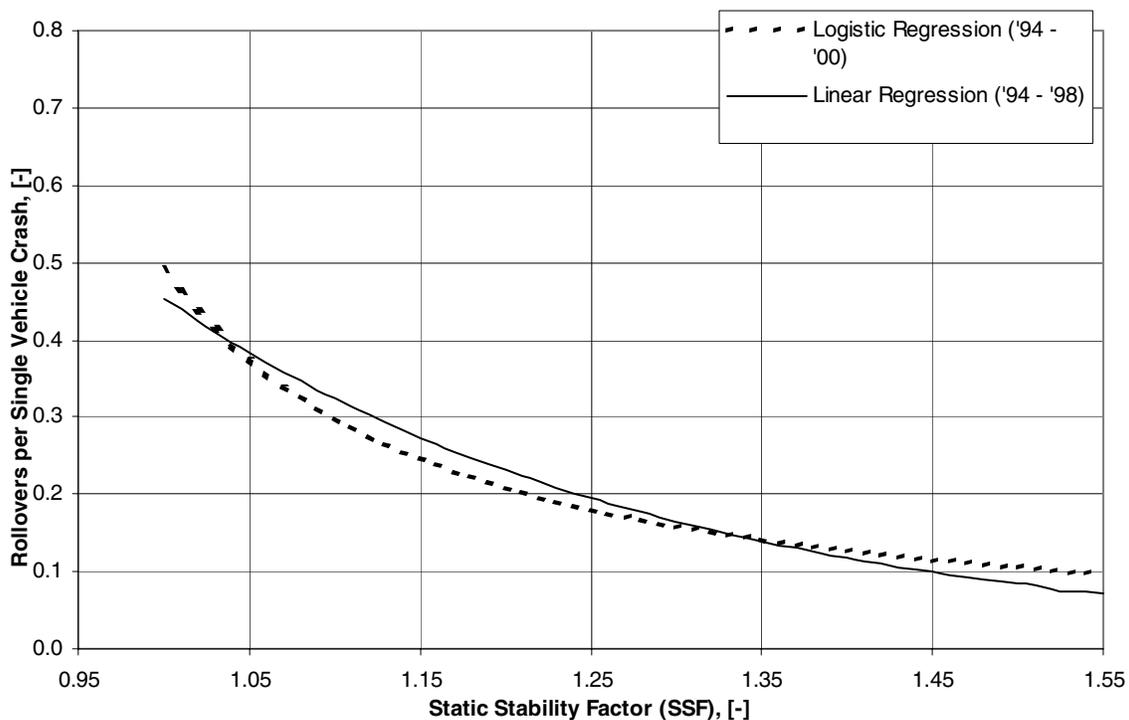


Figure 3. Logistic regression risk model using SSF only and linear regression risk model for 2001-2003 NCAP Rollover Resistance.

First, NHTSA tried each dynamic variable separately in conjunction with SSF. The models using variables for performance in the Fishhook Heavy and J-Turn Heavy maneuvers predicted a greater rollover risk for those vehicles that tipped up in the maneuver test. However, the models using variables for performance in the Fishhook Light and J-Turn Light maneuvers predicted a greater rollover risk for vehicles that did not tip up.

NHTSA does not believe vehicles that tip up in the least severe maneuvers are actually safer than those that do not tip up. A more rational interpretation is that the numbers of vehicle tipping up in these maneuvers were too few to establish a definitive correlation. Only three vehicles tipped up in the J-Turn Light maneuver, and six vehicles tipped up in the Fishhook Light maneuver. Only one more vehicle tipped up in the J-Turn Heavy maneuver than in the Fishhook Light, and the prediction of the model with J-Turn Heavy was consistent with expectations that tip-up in the test predicts greater rollover risk. However, the extra vehicle in the J-Turn Heavy tip-up group was the Ford Ranger 2WD with a very large sample size of over 8,000 single-vehicle crashes (nearly 10 percent of the entire data base).

Next NHTSA computed a logistic regression model combining SSF with the dynamic variables for both maneuvers, Fishhook Heavy and J-Turn Heavy, that were observed to have a directionally correct result when entered into the model individually. The variable for J-Turn Heavy was rejected by the logistic regression program as not statistically significant in the presence of the Fishhook Heavy variable. In other words, the predictions based on tip-up in the Fishhook Heavy maneuver do not change whether or not the vehicle also tips up in the J-Turn Heavy maneuver.

Figure 4 shows the final model that uses Fishhook Heavy as the only necessary dynamic variable. This model has a risk prediction for vehicles that tip up in the dynamic maneuver tests based on the greatest number of vehicles possible in our 25 vehicle data base. All 11 vehicles that tipped up in any maneuver are represented on the tip-up curve, and the 14 vehicles without tip-up are represented on the other curve. The risk curve in Figure 4 representing vehicles that tipped up in the Fishhook Heavy maneuver is very similar to the logistic regression model based on SSF only in Figure 3 (that was based on the rollover rates of 100 vehicles). This result is

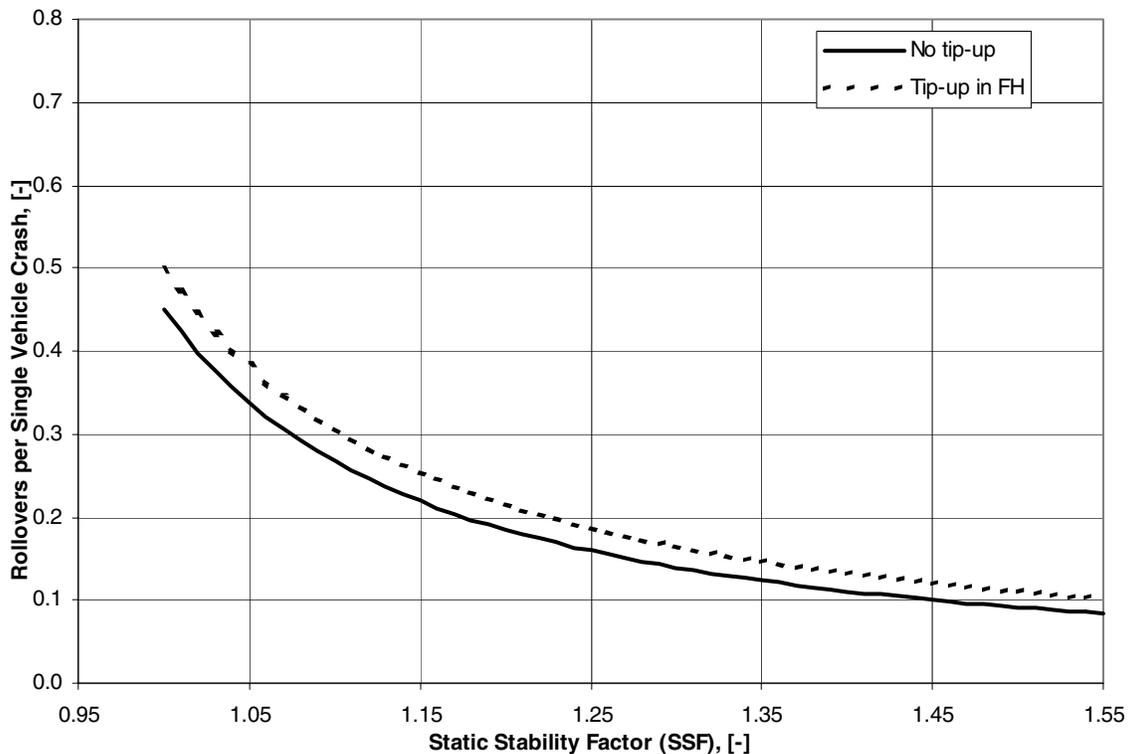


Figure 4. Final dynamic model using Fishhook maneuver with heavy load (FH) as the only necessary dynamic variable.

logical because the SSF only model was optimized for best fit in the 1.00 to 1.25 SSF range that included all vehicles tipping up in dynamic maneuver tests. Also, the fact that the risk curve of the logistic regression model in Figure 3 that was based on the SSF of 100 vehicles closely matches the risk curve in Figure 4 that was based on 11 vehicles that tipped up in the dynamic tests suggests that the curve in Figure 4 is robust. However, the small difference in Figure 4 between the risk curve for vehicles that tip up in the dynamic test and the risk curve for those that do not tip up suggests that the predictive power of tip-up in the dynamic test may not be great.

Our testing and logistic regression analysis was sufficient to assign a greater rollover risk to vehicles that tipped up in the most severe maneuver than to those that did not tip up at all. However, the extra risk was small, and NHTSA were not able to distinguish a rollover risk difference between vehicles that tipped up in the less severe Fishhook maneuver with a two occupant load from those that tipped up only with a five occupant load. In general, vehicles that tip up in the Fishhook maneuver with a two occupant load also tip up at a slower entry speed in the Fishhook maneuver with a five occupant load than those that do not. Therefore, our data does not allow us to distinguish rollover risk differences between vehicles on the basis of maneuver entry speed for tip-up. The objective of using different load conditions and different maneuvers instead of different speeds in a single maneuver to provide a range of test severity was to reduce the sensitivity of the result to differences in pavement friction and to extraneous factors such as tire wear.

It is noteworthy that the final rollover risk model required results from only the Fishhook maneuver. This is an advantage from the standpoint of minimizing the practical problems of the effects of tire wear during a test series and of deviations from uniformity of surface friction at a test facility. The Fishhook maneuver produces less wear on the test tires and requires only about 2 or 3 lane widths of uniform test surface versus 10 or more lane widths for the J-Turn maneuver. The commenters also considered it more representative of a real driving situation than the J-Turn.

CONCLUSIONS

The logistic regression risk model based on SSF only in Figure 3 is practically identical to the rollover rate prediction versus SSF in the final dynamic model of Figure 4 for vehicles that tip up in the Fishhook maneuver. Therefore, the only difference in NCAP

rollover resistance ratings for those vehicles in the new “dynamic” rating system is attributable to the change in analysis technique from linear regression to logistic regression. For vehicles that do not tip up in the Fishhook maneuver, the predicted rollover rate is lower by a modest amount that would increase the “star rating” for the vehicle by somewhat less than “half a star.” This improvement would change the star rating only for those vehicles whose predicted rollover rate would otherwise fall near a “star boundary.” However, the NCAP web site presentation has been revised to show the predicted rollover rate of a vehicle and the range of predicted rollover rates for that class of vehicle as well as its star rating. In that way, the lower rollover risk of vehicles that do not tip up in the Fishhook maneuver is reported even if it did not change the star rating.

REFERENCES

1. Federal Register. 2003. “Final Policy Statement”, Volume 68, October 14, pp. 59250-59304.
2. Hertz, Ellen, “Passenger Vehicles in Untripped Rollovers”, NHTSA Research Note, September 1999.
3. Forkenbrock, G.J., Garrott, W.R, Heitz, M., O’Harra, B.C., “A Comprehensive Experimental Examination of Test Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover – Phase IV of NHTSA’s Light Vehicle Rollover Research Program,” NHTSA Technical Report, DOT HS 809 513, October 2002.
4. Transportation Research Board. 2002. Special Report 265. “The National Highway Traffic Safety Administration’s Rating System for Rollover Resistance: An Assessment”, National Research Council, Washington, D.C.
5. Federal Register. 2001. “Notice of Final Decision”, Volume 66, January 12, pp. 3388-3437.
6. Forkenbrock, G.J., Garrott, W.R, Heitz, M., O’Harra, B.C., “An Experimental Examination of 26 Light Vehicles Using Test Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover – Phases VI and VII of NHTSA’s Light Vehicle Rollover Research Program,” NHTSA Technical Report, DOT HS 809 547, October 2003.

EXPLORATORY STUDY OF THE DYNAMIC BEHAVIOUR OF MOTORCYCLE-RIDER DURING INCIPIENT FALL EVENTS

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ABSTRACT

The continuing study of motorcycle riding gear carried out by Dainese has led to the development of a system of protective riding gear with an integrated air-bag. The aim of this system is not only to reduce the injuries to a rider due to impacts with opposing objects but also to prevent direct contact with the terrain caused by accidental falls.

The scope of this research was to use a multi-body code to simulate the fall of the motorcycle-rider system to determine which parameters can be useful in identifying the early stage of fall. Determining such parameters will be used to develop a logic of control able to activate a passive system of protection, a type of air-bag, included both on the motorcycle and in the rider's protective gear. The rider model was based on a crash test dummy scheme. Dynamic behavior of the system was analyzed in diverse critical conditions. As a result useful information regarding possible crash events was collected.

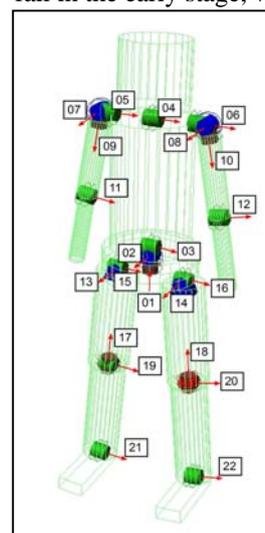
INTRODUCTION

The urge for safety in the automotive field is growing every year, but besides the great efforts put forth in research, there is still much to do. Until significant changes are implemented in road architecture, new strategies will need to be identified for reducing crash related injuries. This is particularly true in the motorcycle field. While in the automotive sector research and regulation had begun to chase safety far in the past, with regard to motorcycles the situation is still in its infancy. Motorcycle safety relies mostly on passive systems. As such, significant safety goals have been achieved in recent years through improvements in riding gear. However there is still much work to do for catching up with the safety levels achieved by cars. With regard to active safety, the principal improvement has been the recent introduction of ABS to various motorcycle models. From the safety regulation point of view, the situation is still unchanged, and effectively we can

say that, in most countries, roads are predominantly made for cars: any other type of vehicle is seen as just a novelty or as something bizarre and unusual. Directly related to this issue many believe that riding motorcycles is excessively hazardous, however this idea can be effectively modified if advances in safety show relevant improvement. Dealing with the motorcycle's related intricacies has always proven complex due to the additional degrees of freedom associated with the vehicle [1]. However this added freedom could offer new possibilities to the crash safety challenge, giving space for new solutions different from those used in the car industry. Two of the more interesting enhancements in passive safety are coming from the air-bag field; both air-bags equipped on vehicles and on riders are being taking into production phase. Currently the two systems are not conceived to work together, but, since they aim to fulfill different targets, this handicap at this stage is acceptable. Vehicle installed air-bags aim to protect the rider in vehicle versus vehicle impact, while rider installed air-bags aim to avoid injury from bodily impact with terrain during single vehicle accidents. As always when dealing with air-bag related problems, one of the biggest challenges is developing the activation algorithm. For vehicle versus vehicle, and vehicle versus object impact, the strategy is already established from the car industry and needs only to be applied appropriately. However with regard to motorcycle single vehicle, loss of control accidents, such a strategy has yet to be conceived. Preliminary steps in defining such a strategy will be the aim of this article.

MODEL OF THE RIDER

Wanting to investigate the dynamics of the fall in the early stage, we shall consider that the



rider is not yet in contact with the road surface. Although some account of the impact aspects of a collision [6] is included, we focused on a multi-body model for dynamic analysis of the motorcycle-rider system. For succeeding in such a task, a rather complex model of the rider was developed. It consists in a total of 13 main and 25 contact bodies, connected together by means of 22 kinematic joints.

Figure 1. Stand alone model of the rider

Using this new rider model in conjunction with an proven multi-body model for motorcycle dynamic analysis, we obtained the starting virtual environment for realizing the various simulations.

Model enhanced features

One of the most difficult tasks met during the realization of the rider model was defining the various body parts and joints in a realistic way. There were several main problems: first, the position to assign to the rider; then, what type of constraints were appropriate for describing the actual rider movement during falls, finally the stiffness and damping to assign to each joint. To find a solution to the problem, we started from the human 50th percentile data and from a rider model developed at the University of Tokyo [3]. We changed many factors to accommodate the new features of our model: we added several d.o.f. and also changed the description of the joints. Another problem needed to be solved, how to link the rider to the vehicle without preventing the freedom of movement needed for this particular simulation. For this purpose, many strategies were tried using different types of time-limited kinematic links, but finally the solution was found using a different approach based on a modified hertzian contact between bodies. We added to the model several contact bodies with the purpose of simulating realistic contact between the rider and the vehicle. These contact bodies also aimed to simulate the typical points of contact between riding protective gear and surroundings. The contact approach had

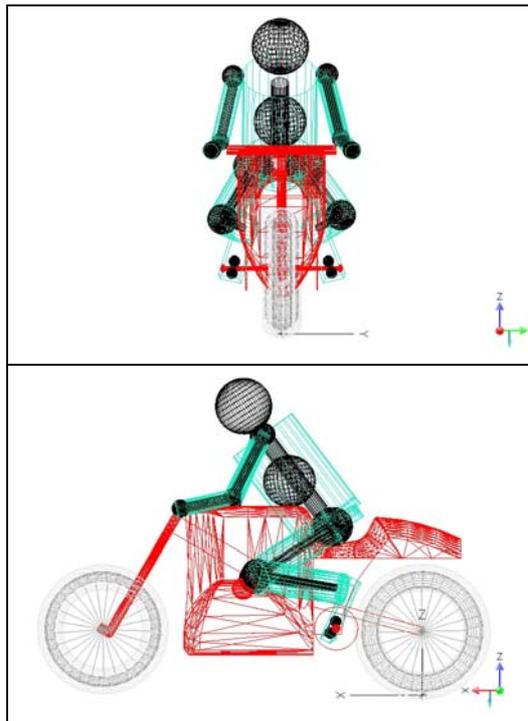


Figure 2. Assembled model with black indicating contact elements.

the disadvantage of slowing down the simulations but fulfilled the other requirements. To realize the appropriate linking condition between the rider and the saddle, a torque exerted by the hip realized the contact between the knees and the fairing.

The ground was modelled as a plane body which generates contact upon penetration by imposing bodies. The tire forces were based on the Pacejka Magic Formula [5], specifically modified to represent motorcycle tires [4]. Care should be taken when viewing crash results since due to the large slip values involved in these type of maneuvers, the tire forces cannot always be considered reliable. Nevertheless we should note that the first instants from the start of the fall are the most important for deciding the subsequent dynamic behaviour of the motorcycle, and at this stage the tire forces are still reliable.

Another consideration that should be done is that the tire parameters change the behaviour of the motorcycle considerably, so a different set of tire parameters can led to different results.

The Control System of the Model

The control system was based on a PD control algorithm, using the roll of the vehicle and the torque exerted through the motorcycle handlebar as working variables.

Basically, depending on the type of maneuver, a roll value is passed to the steer actuator which generates a torque proportional to the gap between the desired roll an the actual roll, with a damping term depending on the rolling speed of the motorcycle.

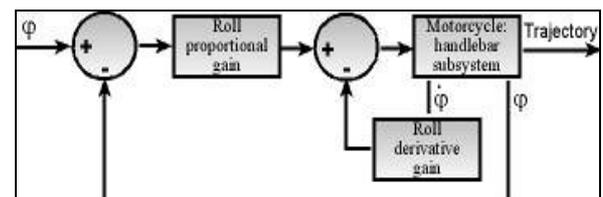


Figure 3. Control system of the virtual model.

This simple scheme can be justified in this context. At this early stage of exploration the goal was not to model the complex relationship between the rider control technique over the motorcycle, rather the focus was that of using the vehicle as a means, letting the rider movements evolve freely in the early stage of the fall. In general, the act of falling implies a loss of control, hence this simple control is sufficient to deliver the model to the desired state. In addition to the basic roll control other auxiliary control routines were introduced, determining factors such the forces exerted between the hands of the rider and the handlebars, and the torque exerted by the hips these subroutine were necessary to take into account the changing

attitude of the rider with respect to the motorcycle control during the simulation. The developed model was used in a series of simulations of critical maneuvers. Three particular cases have been chosen: critical front braking, critical rear braking, and high-side fall.

ANALYSIS OF THE MANEUVERS

The dynamic analysis of a motorcycle is very complex due to its own instability, especially at low speed. Without the rider's control, a motorcycle can fall not only when the motorcycle is stopping but also when it is running in straight uniform motion [2]. We will now investigate the dynamics of the motorcycle when control limits are exceeded and falling is imminent. It is the intent of the following simulations to represent the initial stages of the fall as such the simulation halts when roll angle exceeds 1.3 rad (75 deg).

Case 1: Low-side Fall due to Front Braking

For the following description see Figure 4. We will now consider a motorcycle during a critical braking condition, in which the rider engages the front brake during steady turning, causing the motorcycle to slide off the road. The scenario could be the one of a motorcycle entering in a curve with excessive speed and trying to avoid an unforeseen obstacle.

This type of fall is common among inexperienced drivers. Being unaccustomed to critical driving situations, they react instinctively to the unexpected condition, ignoring the limits of adherence of the tires. Sometimes however this type of fall also happens to experienced driver on unexpected, uneven terrain. In order to get a more clear comprehension of the maneuver the time evolution of the simulation parameters is presented in Figure 4.

Frame A - Shows the initial stage of the maneuver: the motorcycle is running in steady turning at the speed of 40 m/s, the camber angle is about 30°.

Frame B - At this stage the rider starts braking with the front brake only. Due to the braking longitudinal slip, the side force necessary for maintaining equilibrium is obtained with a slip angle greater than the one necessary in curve without the presence of the braking force.

Frame C - The tire reaches its own adherence limit proportional to the normal load, but because of the load transfer suffered by the bike during the braking maneuver, the augmented adherence permits to the rider to maintain control over the motorcycle.

In these conditions it is quite possible for the side force produced by the front wheel to be

insufficient; consequently the front wheel increases its slip angle.

Frame D - The force is still not sufficient to maintain the trajectory so the slip angle continues to increase accordingly. In order to try to follow the desired trajectory, the driver is turning the handlebar with increasing force, but at this point the steering head reach its rotational limit. The force is still not sufficient to maintain the trajectory so the slip angle continues to increase accordingly. Due to the maximum in the vertical force, the lateral force of the front tire also reaches its maximum. An important thing to note at this point is the rapid increase in the roll velocities, this should suggest that the rider is beginning to lose control of the vehicle and is not more able to maintain a determined inclination.

Frame E - With regard to the braking action, the driver can decide to stop or to continue acting on the front wheel in order to get more control of the motorcycle. If the braking action persists the front tire continues slipping to external side.

At this point the front wheel rotational speed is zero, so the front tire is completely sliding.

In the simulation braking continues. The front tire now is almost unloaded, primarily due to the roll angular momentum, as such the lateral force is largely insufficient.

Frame F - The motorcycle tilts and falls laterally. In the fall motion the vehicle also drags the driver down with a certain lag depending on the holding conditions. The simulation ends: fall is in act. If the driver is well protected and other vehicles are not in a collision trajectory, the fall may not be dangerous, in the sense that the motorcycle does not fall against the driver. Eventually injuries could come from the bruising contact with asphalt and any incidental impact with objects surrounding the road.

Case 2: Low-side Fall due to Rear Braking

For the following description see Figure 5. We will now consider a motorcycle braking the rear wheel while in a curve.

The rider maintains the rear braking action for the duration of the simulation. The scenario could be the one of a motorcycle entering in a curve with excessive speed and, trying to avoid entering the opposing lane, the rider applies the rear brake. The rear tire of the simulation encounters a low friction surface, such as dirt or gravel, and loses adherence. This type of fall is less common but also happens to expert drivers.

Frame A - Shows the initial stage of the maneuver: the motorcycle is running in steady turning at the speed of 40 m/s, the camber angle is about 30°.

Frame B - At this stage the rider starts braking with the rear brake only. Due to the braking longitudinal

slip, the side force, necessary for maintaining equilibrium, is obtained with a slip angle greater than the one necessary in curve without the presence of the braking force, consequently the rear wheel increases its slip.

Frame C - The tire reaches its own adherence limit proportional to the normal load. In these conditions it is quite possible for the side force produced by the rear wheel to be insufficient; consequently the rear wheel continues to increase its slip angle. The rider, trying to control the vehicle, rapidly increases the steer angle. Consequently the front slip angle increases.

Frame D - The spin motion of the rear wheel halts, the rear tire now is longitudinally sliding with a speed equal to that of the vehicle.

Frame E - The steer angle reaches the maximum possible. From this point forward the rider is no longer able to maintain a steering control on the motorcycle.

Frame F - Due to the load transfer, the rear tire is now completely unloaded so the possibility of exerting a lateral force no longer exists.

Frame G - Due to the yaw motion the front tire is almost orthogonal to the trajectory. So slip parameters lose sense, the tire behavior in this zone is totally unpredictable.

Frame H - The motorcycle tilts and falls laterally. In the fall motion the vehicle also drags the driver down. The simulation ends.

The closing comments made for “Case 1” apply also in this case.

Case 3: High-side Fall

For the following description see Figure 6.

We will now consider a motorcycle suddenly accelerating during a curve.

The scenario is one of the most common encountered during competition.

The typical occasion when this happens, is when the rider attempts to exit from a curve with maximum velocity. He anticipates more traction than is available, and opens the gas while the motorcycle is still leaned significantly.

Frame A - Shows the initial stage of the maneuver: the motorcycle is running in steady turning at the speed of 40 m/s, the camber angle is about 30°. The rider instantly opens the throttle; the rear tire starts to increase greatly its longitudinal slip while the rear wheel is spinning. The front wheel is also increasing its slip angle because load transfer has already unloaded the front wheel.

Frame B - The rider stops accelerating and releases the throttle. A small quantity of braking torque is present due to the engine braking. The front tire stops increasing its slip angle while that of the rear tire continues to increase. The large side slip, which is still present, generates a lateral force impulse that

is not balanced. The result is that the motorcycle is violently twisted and pushed upwards.

Frame C - The rear tire longitudinal slip goes to zero, hence, as the lateral slip angle grows the lateral force can fully develop as permitted by the Magic Formula. The high-side is in act. The time delay between the two maximums in the slip happens because the longitudinal slip has to decrease below a certain amount to permit the lateral force to grow and to stop the sliding of the tire.

Frame D - The vertical force goes to zero, and the tire loses contact. The steer angle reaches its limit, but the vehicle is still controllable.

Frame E - The handlebar again reaches its limit, the lateral force is now positive to compensate for the steering angle. The motorcycle is weaving about the roll and yaw axes.

Frame F - Another plateau appears in the vertical force, rapidly followed by a new maximum. The motorcycle is oscillating vertically, actuating the rear shock. After having absorbed part of the lateral force caused by the high side, the compression of the spring is released, projecting the rider upwards.

Frame G - The rider is now almost totally separated from the motorcycle, and is ejected skyward.

Frame H - The simulation ends. The vehicle is almost completely tilted and the rider is jettisoned from the motorcycle. In this particular simulation the roll velocity of the rider and that of the vehicle are opposite.

With particular attention to Figure 7, we can describe the initial phases of the high-side. From A to B we see the response to the instantaneous acceleration. The tire reaches the boundary of the traction ellipse, this represents the saturation limit of the forces. Moving toward condition B, as the slip continues to increase, first the force reaches its saturation limit and immediately after starts to decrease (Pacejka model). From here over, the high slip produced in the thrusting phase starts to generate an impulsive lateral force, which reaches the maximum at C. The lateral force generated in this manner is mostly unbalanced, so the vehicle starts tilting in the opposite direction. If the lateral impulse is high enough, the motorcycle falls immediately; if it is not the vehicle starts weaving and depending on the ability of the rider, control over the vehicle can be regained, otherwise a fall is imminent.

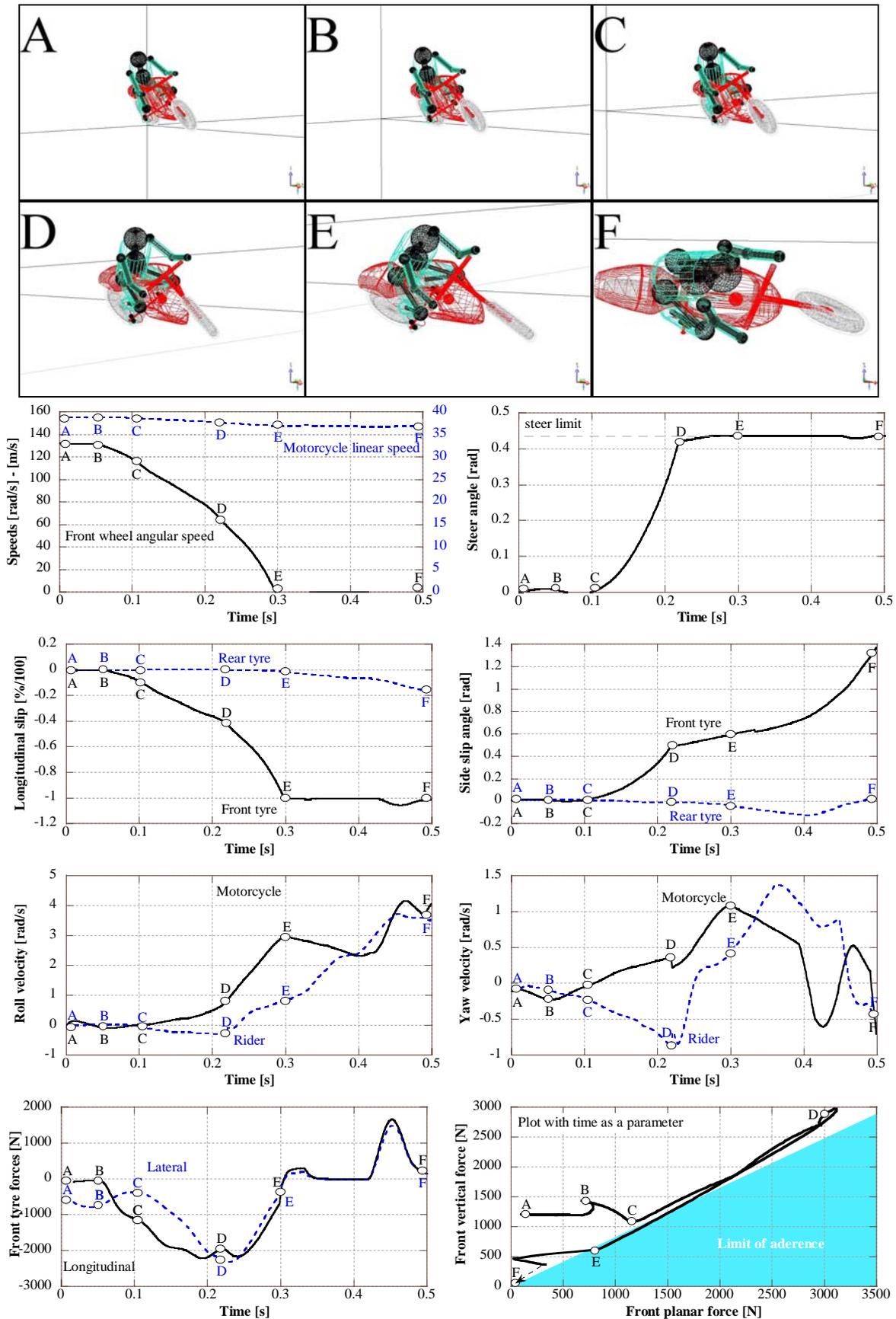


Figure 4. (Case 1) Top, six views of the simulated environment; Bottom, plots of different simulated quantities: motorcycle speed and front wheel speed, steer angle, longitudinal slip, slip angle, roll velocity, yaw velocity, tyre forces.

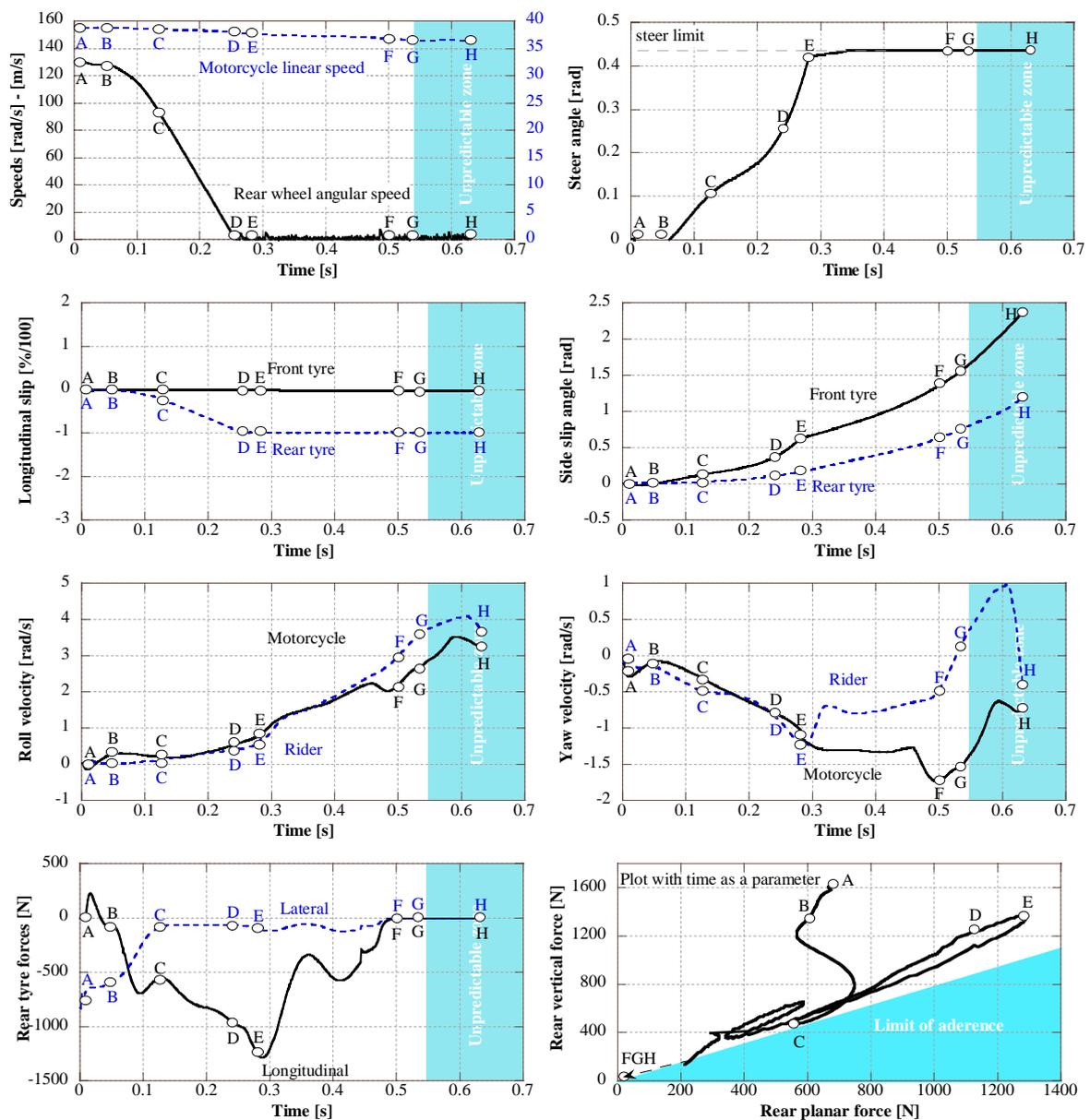
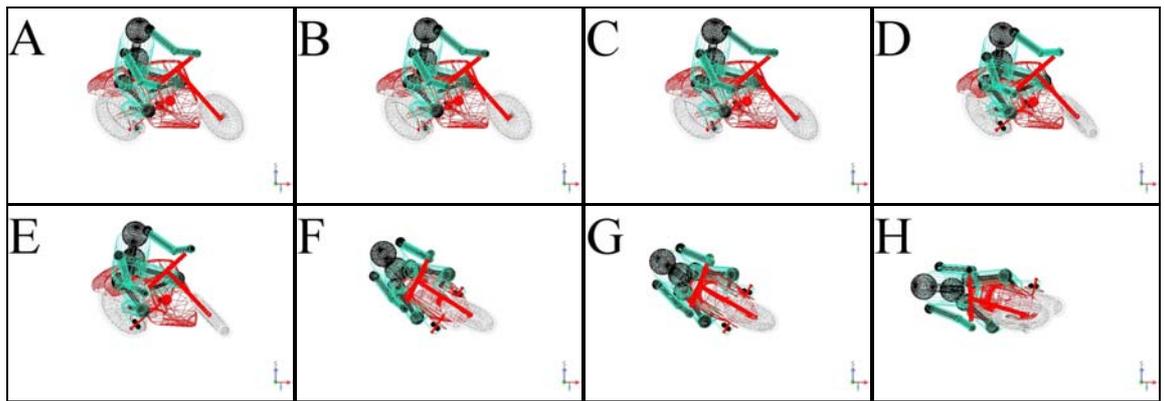


Figure 5. (Case 2) Top, eight views of the simulated environment; Bottom, plots of different simulated quantities: motorcycle speed and front wheel speed, steer angle, longitudinal slip, slip angle, roll velocity, yaw velocity, tire forces.

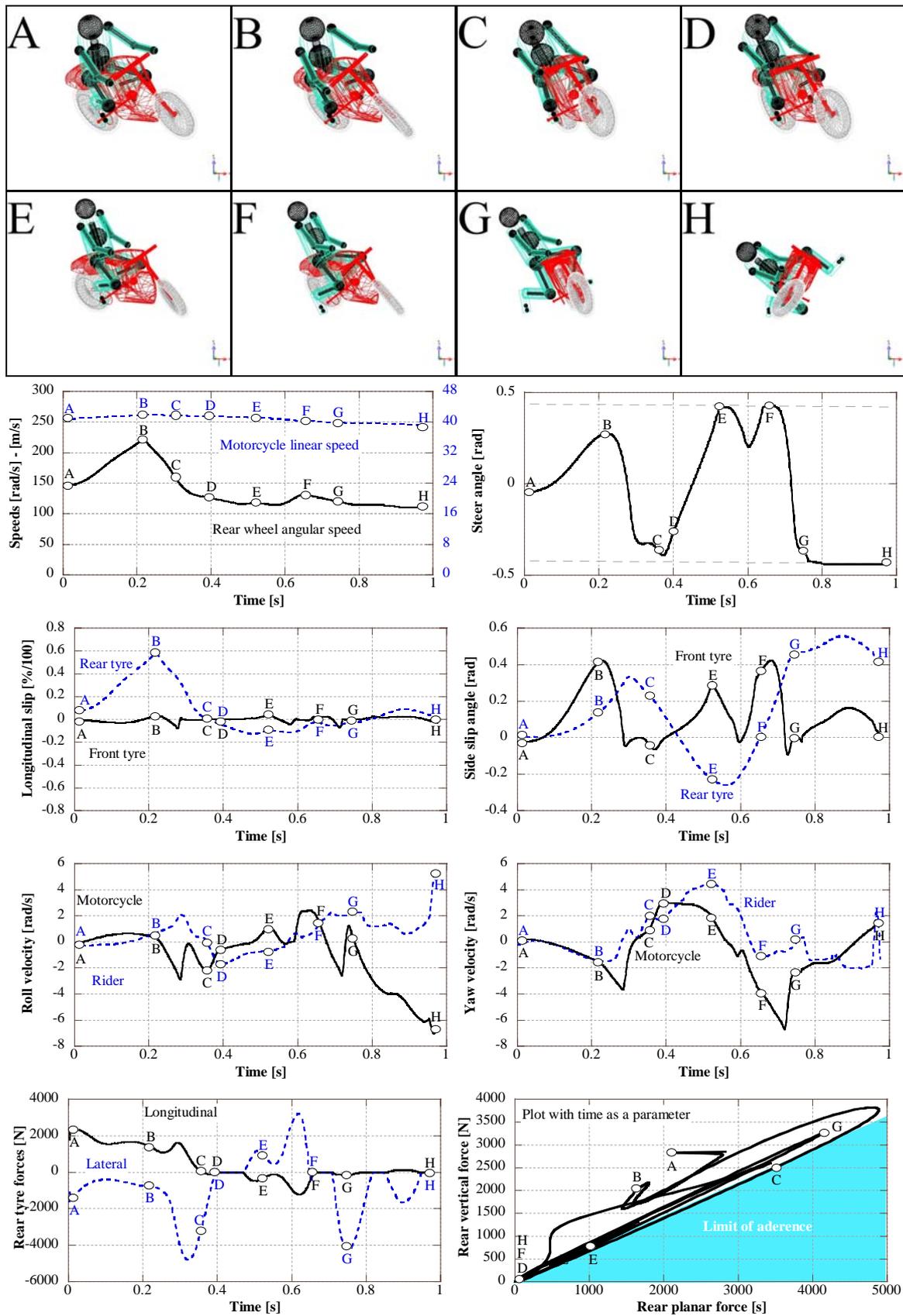


Figure 6. (Case 3) Top, eight views of the simulated environment; Bottom, plots of different simulated quantities: motorcycle speed and front wheel speed, steer angle, longitudinal slip, slip angle, roll velocity, yaw velocity, tire forces.

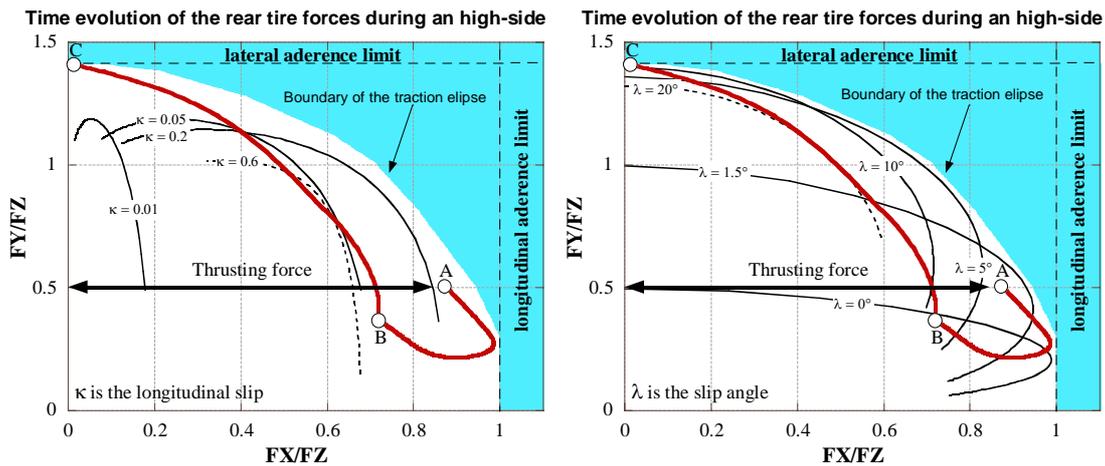


Figure 7. (Case 3) This graph show the time evolution of a high-side with reference to the traction ellipse.

CONCLUSIONS

This exploratory study hoped to improve our knowledge of dynamic behavior of motorcycle-rider system during critical conditions, and to further identify some parameters which could be used to improve actual active and passive safety system. Although additional work will be needed to solidify this cause, the current study is an attempt to mark the first steps in the right direction. Three simulation cases are summarized and a number of relevant parameters are shown. These parameters may prove useful in determining the control algorithm for a multi purposes air-bags deployment system.

The current study also shows that great advantages can be gained by using multi-body modeling to simulate complex dynamics systems. Although the computational burden of these simulations is still high, such tools can certainly be used to reduce, or at least give direction to, the number of expensive (and sometimes dangerous) experimental tests which must be carried out for fulfill the design process.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Cossalter, V. 2002. "Motorcycle Dynamics". Race Dynamics.
- [2] Cossalter, V., R. Berritta. 1999. "Analysis of the dynamic behaviour of motorcycles in dangerous manoeuvres using the multi-body code MSC

Working Model." In Proceeding of the 1999 High-tech Engine and Cars Conference (Modena, Italy).

- [3] Imaizumi, H., T. Fujioka and M. Omae. 1995. "Rider model by use of multibody dynamics analysis." JSAE Reviews 17 (1996) 65-77.
- [4] Lot, Roberto. 2004. "A Motorcycle Tire Model for Dynamic Simulations: Theoretical and Experimental Aspects", Meccanica Vol. 39: 207-220.
- [5] Pacejka, H. B. 2002. "Tyre and Vehicle dynamics", Butterworth-Heinemann, Oxford
- [6] Silva, M.P.T., J.A.C. Ambrosio and M.S. Pereira. 1996. "Biomechanical Model with Joint Resistance for Impact Simulation." Multibody System Dynamics 1 (1997) 65-84.

Safety and Performance Enhancement: The Bosch Electronic Stability Control (ESP)

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Paper Number 05-0471

Product (GDP) [1]

ABSTRACT

In spite of improvements in passive safety and efforts to alter driver behavior, the absolute number of highway fatalities in 2002 increased to the highest level since 1990 in the US.

ESP is an active safety technology that assists the driver to keep the vehicle on the intended path and thereby helps to prevent accidents. ESP is especially effective in keeping the vehicle on the road and mitigating rollover accidents which account for over 1/3 of all fatalities in single vehicle accidents.

In 1995 Bosch was the first supplier to introduce electronic stability control (ESC) for the Mercedes-Benz S-Class sedan. Since then, Bosch has produced more than 10 million systems worldwide which are marketed as ESP - Electronic Stability Program.

In this report Bosch will present ESP contributions to active safety and the required adaptations to support four wheel driven vehicles and to mitigate rollover situations.

INTRODUCTION

Worldwide traffic is increasing with more and more vehicles on the road. Considering the different regions of

the world, the development of the mobility shows a clear correlation to the gross domestic product (Fig. 1). With further economical growth, we will see more increase in mobility and in traffic density throughout the world. This will require additional efforts to furthermore enhance the road safety.

The statistics for the European Union demonstrate alarming results. They show a total of 1.3 million accidents for the year 2000 with 1.7 million injured persons and more than 40.000 fatalities. The target of the eSafety Initiative of the European Union for 2010 is set to reduce road deaths by 50%, e.g. by the promotion of intelligent active driving safety systems (Fig. 2).

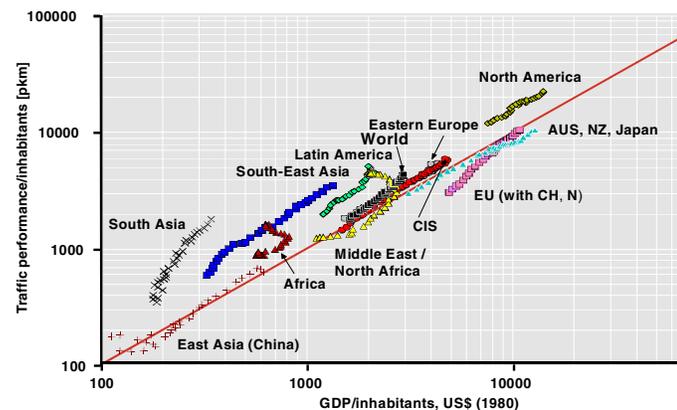
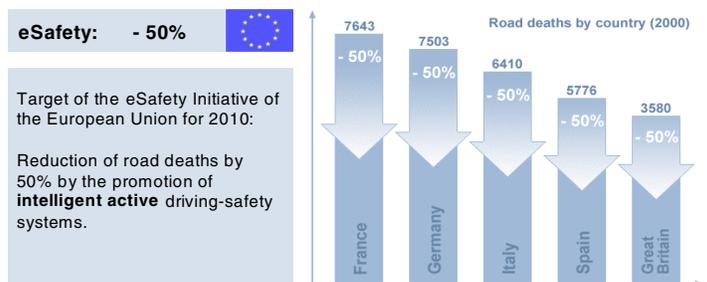


Fig. 1: Development of mobility depending on Gross Domestic



Traffic safety situation European Union (status year 2000):
1 300 000 accidents, 40 000 deaths, 1 700 000 injured

Fig. 2: European eSafety initiative

Japan has set a similar target and also NA is actively pursuing advances in road safety.

MAIN SECTION

The progress of crash energy absorbing car body design and the standard fitting of airbags significantly improved the passive safety especially combined with the use of seat belts. But many of the serious accidents happen through loss of control in critical driving situations. When the vehicle goes

into a skid, a side accident is the frequent result. With a reduced protection zone for the occupants compared to front crashes, these accidents show an amplified severity.

Especially with vehicles of an elevated center of gravity like sport utility vehicles (SUV) and light trucks (LT) the loss of control with subsequent skidding may even lead to a rollover. Most of the rollovers are caused either by tripping at an obstacle or in the soil. The severity of rollover accidents is extremely high. Accounting for only 2% of the total crashes, they contributed in 2002 with 10.656 fatalities to one third of all occupant fatalities (Fig. 3) in the US.

US Accident fatality statistics

Total Accidents		Fatalities	
Involved Vehicles:		Occupant Fatalities:	
10.6 Mio		32.335	
Point of Impact		Severity (by fatalities)	
Frontal crash:	46 %	Frontal crash:	39 %
Side crash:	29 %	Side crash:	23 %
Rollover:	2 %	Rollover:	33 %

Fig. 3: North America accident fatality statistics

A study performed by the University of Iowa at the National Advanced Driving Simulator showed a strong impact of ESP on vehicle stability [2]. The primary question was “Does the presence of an ESP system aid the driver in maintaining control of the vehicle in critical situations?”. Based on all analyses completed there was a 24.5 percentage point reduction between situations in which the drivers lost control with the system present and situations without ESP. This constitutes an 88% reduction in loss of control. Looking at the data from an improvement standpoint, 34% more drivers retained control with ESP than without. Based on the study results it was concluded that there is significant and meaningful safety benefit associated with driving a vehicle equipped with an ESP system.

Supporting conclusions are drawn by VW [1]. Based on their accidentology, ESP is considered to avoid 80% of the accidents caused by skidding. VW concludes that the safety benefit of ESP is even greater than that of the Airbag. According to VW a 100% installation rate would result in Germany in a 20% reduction of road fatalities and this even with an ESP installation rate of already 53% in 2003.

Based on the analysis of traffic accidents statistics, Toyota [3] estimated that the accident rate of vehicles with ESP for more severe accidents is approximately reduced by 50% for single car accidents and reduced by 40% for head-on collisions with other automobiles. The casualty rate of vehicles with ESP showed approximately a 35% reduction for both types of accidents.

The results of the studies show a consistent picture of the ESP with remarkable safety benefits. Further potential is available especially with functional extensions for SUV and light trucks concerning rollover mitigation and four wheel drive adaptations.

However it is important to say that ESP cannot prevent all accidents or adjust for all driver errors. Essential for a safe road traffic are still appropriate driving practices, common sense and a good traffic judgement.

STABILIZING CONCEPT

In critical driving situations most drivers are overburdened with the stabilizing task. According to Foerster [4] the average driver can neither judge the friction coefficient of the road nor the grip reserves of the tires. The drivers are typically startled by the altered vehicle behavior in in-stable driving situations; as a result, a well-considered and thought-out reaction of the driver can not be expected. For that reason the ESP has to be designed to stabilize the vehicle even in situations with panic reactions and driving failures like exaggerated steering.

The reason why stabilizing a vehicle in critical situations is so challenging can be shown by considering the physical effects. Steering of a vehicle yields in a yaw moment which results in a directional change. The effect of a given steering angle depends on the actual side slip angle [5, 6]. Only slight alterations of the yaw moment are possible at large side slip angles even for extensive steering interventions which can be seen in Fig. 4.

The characteristic side slip angles, where the steerability of the vehicle is vanishing, are dependent on the road friction coefficient. On dry asphalt it is around $\pm 12^\circ$ as shown in Fig. 4, whereas on polished ice it is in the range of $\pm 2^\circ$. The driver experiences in all day traffic situations side slip angle values of typically not more than $\pm 2^\circ$.

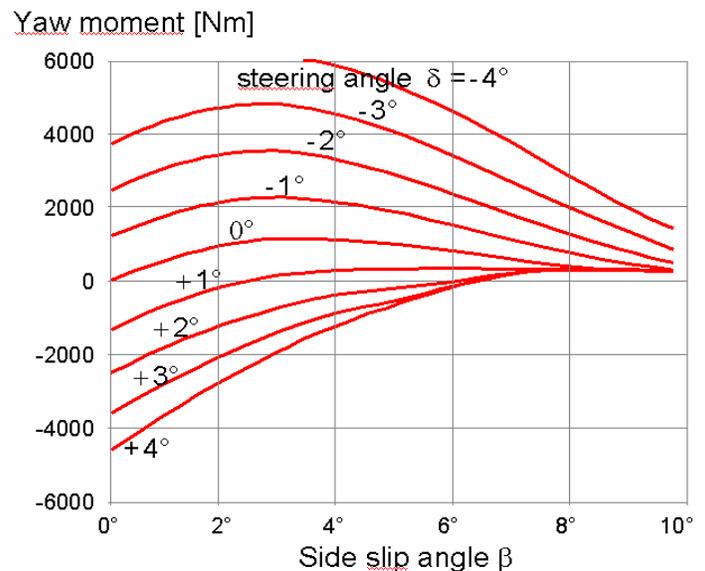


Fig. 4: Influence of side slip angle on yaw moment for different steering angles at high tire-road friction [5, 6].

So one of the main tasks of ESP is the limitation of side slip angle dependent on the actual friction coefficient.

Even in the range of characteristic side slip angles, where the effectiveness of steering is rather limited, ESP can exercise remarkable yaw moments by brake interventions. The tire characteristic determines the longitudinal slip value λ_0 where the maximum brake force is generated. The slip value λ_0 is typically in the range of 10%. Considering the left front wheel during right hand cornering (Fig. 5, wheel 1), the resulting wheel force in free rolling condition $F_R(\lambda=0)$ is in lateral direction. By adjusting the tire slip to λ_0 , the maximum brake force $F_B(\lambda_0)$ is applied and by this means the lateral force is reduced to $F_S(\lambda_0)$. The resulting force vector $F_R(\lambda_0)$ is turned relative to the tire thereby modifying the yaw moment, the longitudinal and the lateral forces.

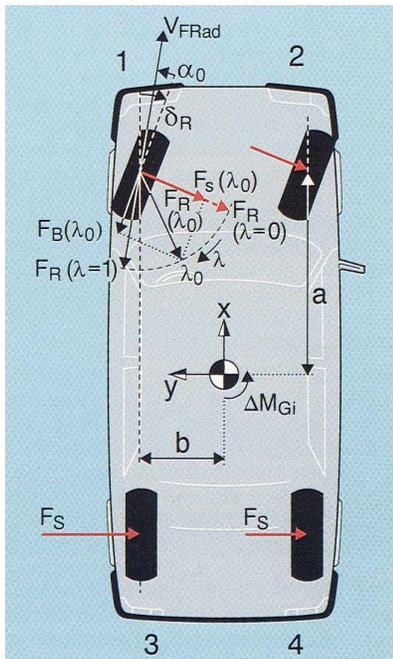


Fig. 5: Turning of resulting wheel force by tire slip control.

The required yaw moment can be applied by controlling the longitudinal tire slip and in that way employing it as a vehicle dynamics control variable. This approach is utilized with anti-lock and traction slip control, yaw rate control with restricted side slip angle and with a limitation of lateral acceleration for rollover mitigation functionality.

During the last few years the segment of four wheel driven vehicles got more and more popular. The main focus of attention is the range of SUV and LT vehicles that are suitable for use on public roads but also have qualities under off-road conditions. Part of the off-road capacities are due to the elevated center of gravity which augments the susceptibility to rollover. This makes SUV and LT the preferred target for ESP applications.

Special adaptations of the ESP system and the control concept are required for the cooperation with a four wheel drive (4WD) power train.

ADAPTATIONS TO FOUR WHEEL DRIVE

Several center coupling concepts are used in the various types of four wheel driven vehicles. Most of them can be combined with an ESP system.

The major element of a four wheel driven (4WD) vehicle is the center coupling. The objective is to distribute drive torque to the front and rear axle and at the same time to permit different axle velocities that occur as soon as the vehicle drives around a bend (Fig. 6).

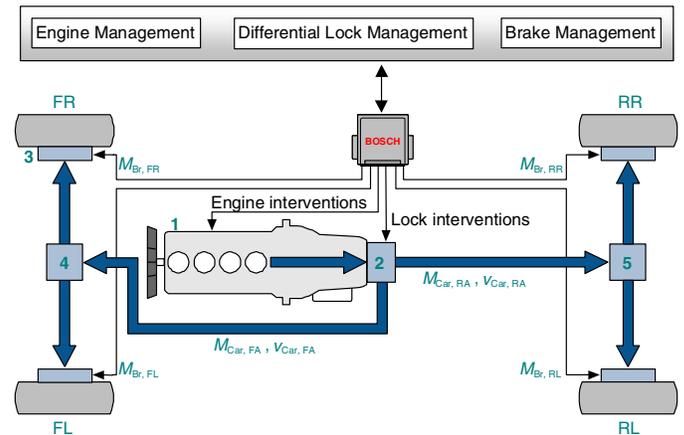


Fig. 6: Control concept for four wheel drive trains with engine (1), center coupling (2), brake (3), differential front/rear axle (4/5).

The classic solution for a 4WD drive train is the open center differential. Its disadvantage is - analogous to a transversal axle differential - the drive torque limitation of an axle if the other one shows increased slip. In the worst case a 4WD car with an open center differential does not move if only one wheel is spinning.

With an ESP system available, this drive train concept can be supported by the brake interventions of the traction slip control without the necessity to install additional longitudinal and transversal lock devices (Fig. 7). The longitudinal differential lock controller in the ESP restrains the difference speed between both axles through a symmetric brake intervention on both wheels of one axle. The transversal differential lock controls the difference speed on one axle through wheel individual brake interventions.

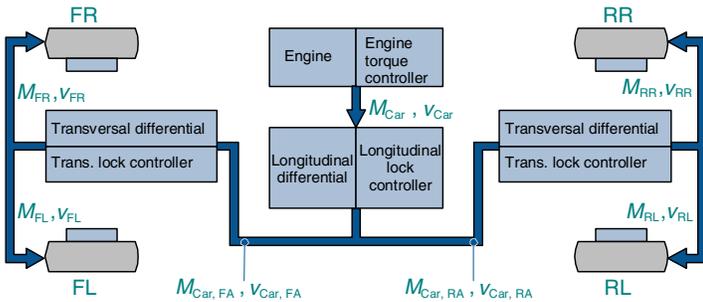


Fig. 7: Four wheel drive with longitudinal and transversal brake lock

Another class of differential locks or center couplings are self-locking devices, where the locking degree depends on torque or rotation speed differences between the two driven axles. Examples are Torsen - for Torque-sensing - or viscous coupling. If their locking potential is exceeded, the above described longitudinal differential lock via brake intervention will support and secure the lock functionality.

A 100% mechanical differential lock is useful for heavy off-road applications, as it prevents any axle speed differences. Since ESP relies on a wheel individual slip control, a cooperation with a mechanically locked center differential is not feasible unless the lock is opened either manually or electronically. Even anti-lock control (ABS) is deactivated or distinctively reduced.

Apart from the mentioned devices that have a system inherent locking effect, there are center couplings that can be fully influenced by an external controller – so called Center Coupling Control (CCC). In this case an electric or hydraulic actuator operates a clutch, providing adjustable locking torque. In combination with vehicle dynamics signals, as vehicle speed and wheel speeds, yaw rate, lateral acceleration and engine torque, the locking torque can be adjusted to tune to the desired vehicle dynamics behavior suitable for the specific driving conditions (Fig. 8).

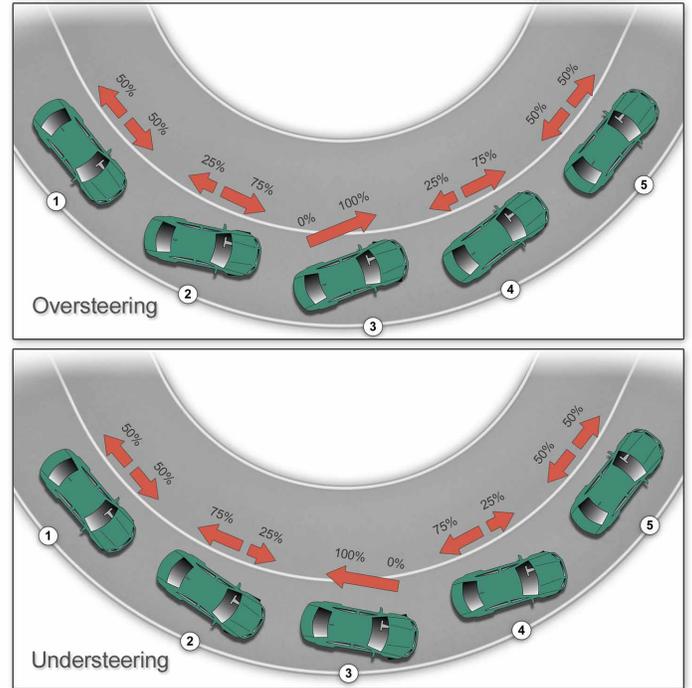


Fig. 8: Influence of drive torque distribution on vehicle dynamics behavior like over-steering and under-steering. Shown is the maximum possible flexibility of drive torque distribution; actual flexibility depends on drive train configuration.

Even in critical driving situations the variable drive torque distribution can positively influence the road behavior of the vehicle. By shifting drive torque to the rear axle, the understeering behavior of a vehicle can be reduced; by shifting drive torque to the front axle, the oversteering behavior can be trimmed down (Fig. 8). Overall a more responsive vehicle handling can be achieved.

The ESP is well suited to extend the brake and engine torque interventions with a center coupling torque interface to optimize the dynamic behavior of the vehicle. One example is shown in Fig. 9. The ESP detects an understeering situation and requests a reduction of the coupling torque transferred to the front axle. Beside this drive torque transfer an additional ESP brake intervention on the curve inner rear wheel supports in case of strong understeering to achieve the desired vehicle yaw rate.

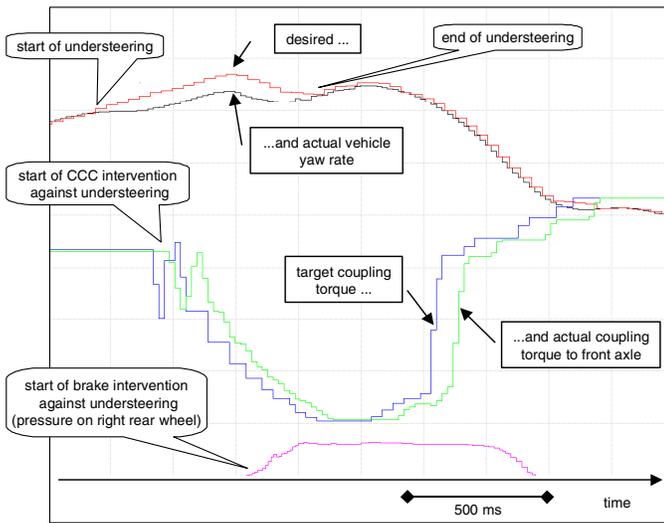


Fig. 9: Understeering intervention with a shift of drive torque followed by a supporting brake intervention. Sporty SUV vehicle with 4WD, center coupling control and ESP8.

For vehicle dynamics and traction optimization a controllable, well defined opening and closing of the coupling is necessary.

On the other hand, during a wheel individual brake intervention, a fully or partially locked center coupling would result in an unintended torque transfer. Therefore a fast opening must also be demanded during stabilizing brake interventions and an active ABS function. In some instances, it may also be necessary during partial braking to allow the “Electronic Brake Distribution” function to prevent the over-braking of the rear axle. This requires the clutch to be opened in less than 100ms.

Additional adaptations support off-road functionality. The off-road features of the ESP controller improve robustness and maintain superior traction under off-road conditions.

These features are:

- Adaptation of start of control thresholds for vehicle dynamics under off-road conditions; increased yaw rate target allowed.
- Self tuning of traction target slip dependent on the road surface and terrain.
- Lessening of engine torque reductions to maintain traction even under difficult drive conditions.
- Adaptive pre-control for the brake torque controller.
- Enhanced vehicle speed estimation under off-road conditions even without use of longitudinal acceleration sensor.
- Robustness measurements for the ABS controller with increased target slip under off-road conditions.

The off-road situation can be detected automatically by a special function of the ESP. Based on wheel speed sensor signals, the off-road detection function analyses wheel excitations and looks for specific oscillations in the wheel

circumference speed. Alternatively the driver may select the off-road adaptations via a switch setting, the activation of a countershaft gearbox or the vertical adjustment of a level control system.

In powerful ESP systems for 4WD vehicles, even different performance settings can be selected by the driver. This can be as simple as disabling the engine torque reduction triggered by the ESP to allow for full driver control of the propulsion. Other possibilities are terrain specific adaptations to surfaces like ice, snow, grass, sand, mud or bedrock.

Some drive train concepts allow a flexible configuration by switching from rear wheel drive or front wheel drive to 4WD. Even 4WD with locked center differential is possible. With a cooperating ESP system, the stabilizing and traction control functionality can be automatically adjusted to the selected drive train concept.

In cooperation with four wheel drive train concepts, ESP delivers the expected safety benefits and excellent off-road functionality. Since most of the respective vehicles are characterized by an elevated center of gravity, road safety can be further improved by implementing rollover mitigation functionality.

ROLLOVER MITIGATION

The complex events of automobile crashes involve three main contributing factors and their interactions [7]:

- the driver,
- the driving environment like weather, road condition, time of day,
- and the vehicle.

In the US, about 10% of all road accidents are non-collision crashes, but approximately 90% of such single-vehicle crashes account for fatalities [8]. The SUV and LT with their elevated center of gravity (CoG) show an amplified rollover propensity. This is reflected in their increased rollover rates. Due to the ever increasing popularity of these vehicles, the percentage of fatal rollover crashes escalated significantly within the last decade.

A vehicle rollover occurs when the lateral forces create a large enough moment around the longitudinal roll axis of the vehicle for a sufficient length of time.

Critical lateral forces can be generated under a variety of conditions. The vast majority of rollover crashes take place after a driver lost control over the vehicle. By skidding off the road, the vehicle may get in lateral contact with a mechanical obstacle like a curb, a pot hole or a plowed furrow which yields a sudden large roll moment. This results in a so called tripped rollover in contrast to an un-tripped or friction rollover. The latter takes place on roads during severe steering maneuvers solely as a result of the lateral cornering forces.

Although the ratio of un-tripped to tripped rollovers is small, the un-tripped rollovers account for the most severe crashes.

Accident analysis has shown that the ratio of the track width T and the height of the center of gravity h_{CoG} gives a first indication for the rollover propensity of vehicles.

$$SSF = \frac{T}{2 \cdot h_{CoG}} \quad \text{Static Stability Factor}$$

The SSF is an important parameter affecting vehicle rollover risk and is both relevant for tripped as well as un-tripped rollover. The track width is a fixed parameter while the center of gravity height varies with subject to different load conditions. Through a one rigid body model - which means no distinction between the mass of the chassis and the sprung mass of the vehicle body - the SSF relates geometrical vehicle data to the level of lateral acceleration that will result in a rollover.

A one rigid body model cannot predict time dependent details of an on-road rollover critical situation. For transient maneuvers involving high lateral accelerations, many vehicle design parameters have an effect on the vehicle handling behavior like e.g. front to rear roll couple distribution, roll axis location, tire behavior, suspension characteristics and roll resonant frequency. These handling characteristics significantly influence the ability of the driver to maintain control in an emergency situation.

To assess a vehicle's handling performance with reference to rollover, the SSF is complemented by metrics derived from dynamic testing which can be partially influenced by electronic stability control. In the US, beginning with the rollover ratings for model year 2004, the National Highway Traffic Safety Administration (NHTSA) will combine the SSF measurement of the vehicle with the dynamic performance in the so-called fishhook or road edge recovery maneuver [8].

To improve the relationship between the real world rollover risk and the SSF-based rollover prediction, the NHTSA defined a new indicator called Rollrate.

$$Rollrate_{SSF} = \frac{1}{1 + e^{(c_1 + c_2 \cdot \ln(SSF - 0.90))}}$$

The parameters $c_1=2.7546$ and $c_2=1.1814$ are derived from a detailed analysis of U.S. crash data using a logistic regression model.

Based on the result of the dynamic test, the static Rollrate value is either increased or decreased. In case of a positive test result, the Rollrate is evaluated with the parameters $c_1=2.8891$ and $c_2=1.1686$ based on crash data analysis; for a failed test, the parameters are $c_1=2.6968$ and $c_2=1.1686$.

Therefore, the dynamic Rollrate replaces the static SSF to get the star rating for a single vehicle according to the following table (Fig. 10).

Star	New criterion:		Previous:
	Rollrate	in terms of SSF:	SSF
**** *	≤ 0.1	≥ 1.4532	> 1.45
****	in [0.1; 0.2]	in [1.1764; 1.4531]	in [1.25; 1.44]
***	in [0.2; 0.3]	in [1.0743; 1.1763]	in [1.13; 1.24]
**	in [0.3; 0.4]	in [1.0194; 1.0742]	in [1.04; 1.12]
*	> 0.4	≤ 1.0193	< 1.03

Fig. 10: NHTSA star rating in case of a positive dynamic test compared with the previously static SSF rating only. Table derived from [8].

If the Fishhook test is passed successfully due to a highly effective vehicle stabilizing system, the corresponding Rollrate may result in a better NHTSA star rating compared with the static evaluation only and more, the rollover risk for the vehicle is essentially reduced.

The load condition influence on the rollover propensity is shown in figure 11 in a simplified manner for different types of cars and loading conditions. The static stability factor for typical passenger cars is far above the lateral acceleration which can be transferred by the maximum tire grip. This is the reason why passenger cars are usually not subject to un-tripped rollovers even in extreme loading conditions. If the adhesion limit between the tires and the road surface is reached before the lateral acceleration gets rollover critical, the vehicle starts to skid over the front wheels.

The situation is different especially for light commercial vehicles, where elevated loading may play a major role.

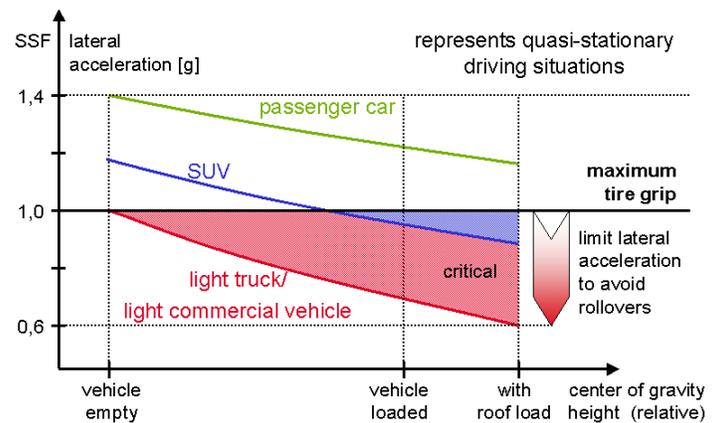


Fig. 11: Typical critical lateral accelerations for rollover dependent on loading conditions reflecting different types of vehicles

At the physical limit the tire behavior is extremely nonlinear and the linearized tire-wheel-brake system is even unstable. As a result, the vehicle may suddenly spin and the driver is caught by surprise.

Changing the direction of the resultant tire forces of individual wheels by specific wheel slip demands applies a stabilizing yaw moment (see Fig. 5). Besides standard ESP, active steering can be used as well to increase the vehicle's tracking stability [9]. Both concepts mentioned as well as

Active Roll Control [10] or Electronic Damper Control [11] can in general help to avoid critical situations and as a result indirectly help to reduce the rollover risk.

Besides the classification according to the rollover reason, rollover scenarios can be divided into highly dynamic maneuvers, e.g. obstacle avoidance, or quasi stationary maneuvers like circular driving with steadily increasing steering wheel angle. The latter can arise while driving on a highway exit with excess speed.

The Bosch Rollover Mitigation Functions (RMF) are based on the standard ESP sensor set and provide a scalable structure concerning the determination of rollover critical situations and brake/engine control (Fig. 12). Other solutions additionally use a roll rate sensor [12].

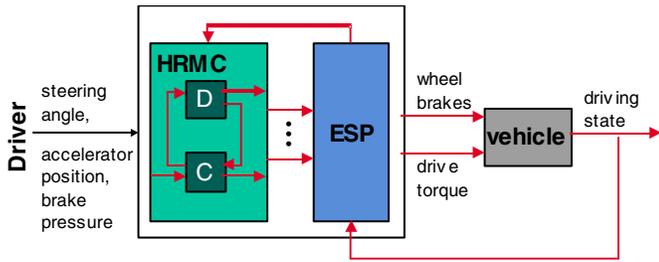


Fig. 12: Structure of the entire vehicle stabilizing system with the basic Electronic Stability Program ESP and the Hybrid Rollover Mitigation Controller (HRMC) with discrete (D) and continuous (C) dynamics parts.

Considering well-known obstacle avoidance maneuvers or severe steering maneuvers like the NHTSA “Fishhook”, a classification can be made in

- first turn maneuvers* (e.g. J-turn, decreasing radius turn, first steering input of single or double lane change, or NHTSA Fishhook),
- second turn maneuvers* (constant radius turn with additional steering input, second steering input of a single or double lane change, or NHTSA Fishhook), and
- further turn maneuvers* (third or further steering input of a double lane change or slalom).

Each turn or even a subset of the corresponding time interval is characterized by a set of typical driver’s inputs as well as a typical vehicle response. Consequently, each dynamic steering maneuver can be divided into several time slots which follow each other in a specific manner. To get an appropriate stabilization, the controller must provide suitable intervention strategy and strength for each of the described phases.

This is why for the detection of severe steering maneuvers and a suitable anti-rollover control, a hybrid dynamical system is used (Fig. 12). The input, output and state of such a system is composed of a discrete and a continuous part; the discrete dynamics **D** and the continuous dynamics **C** are connected by adequate interfaces (for details on hybrid dynamical systems, e.g. see [13]).

The discrete states represent the different defined phases within highly-dynamical steering maneuvers: one possible set of discrete states comprises

- an *Initial* state taken if no roll-stabilizing intervention is necessary
- a *Pre-fill* state to apply the brake pads to the brake discs thereby reducing the pressure build up time,
- a *Hold* state for *first turn maneuvers* with a high lateral acceleration,
- a *Steer-back* state with special pre-fill measures for steering back in highly dynamical maneuvers, and
- a *Counter-fly* state for the second steady steering interval in multi-directional maneuvers.

Transitions between the discrete states are essentially influenced by the driver’s input and the vehicle reaction. Continuous states vary over time dependent on the discrete state. They are influenced by continuous inputs like the steering wheel angle, the lateral acceleration, the yaw rate, the longitudinal velocity, the body slip angle, and other reference variables essential for the rollover prediction. Ackermann and Odenthal propose a rollover coefficient based on the tire vertical loads [9] which are usually not available in a standard ESP systems with the required accuracy. The Bosch approach uses only existing sensor signals and estimated values to predict the vehicle’s rollover propensity. For example, based on the well-known single-track model, an early lead for a subsequent high lateral acceleration is given by

$$c_{pre} = \dot{\psi} \cdot v_x - a_y \approx -\dot{\beta} \cdot v_x$$

- $\dot{\psi}$: yaw rate
- v_x : longitudinal velocity
- a_y : lateral acceleration
- $\dot{\beta}$: change in body slip angle

With a rapid change of the body slip angle weighted with v_x , the lateral acceleration will heavily increase short after.

The Hybrid Rollover Mitigation Controller outputs derived from its states are e.g. the brake torque and brake slip values for the appropriate wheels. The general control strategy is a fast active brake pressure increase at the curve outside wheels especially at the front axle initiated by suitable brake slip and brake torque target values. This reduces the lateral forces as well as the longitudinal speed of the vehicle and results in an increased curve radius. Subsequently the track can be regained due to the reduced speed. In these special situations the brake intervention is usually combined with a cut back on engine torque.

In general, the hydraulic braking system must provide a fast pressure increase over a wide temperature range. For that, the brake caliper size, the brake tube dimensions, and the characteristics of the utilized brake fluid are very important.

As an example, a NHTSA Fishhook maneuver with a sporty SUV model is taken to illustrate the rollover mitigation by a hybrid controller (Fig. 13). The steering input is depicted in terms of steering wheel angle whereas the vehicle reaction is

expressed in terms of lateral acceleration and yaw rate. The stepped variable at the top of the chart indicates the discrete states of the hybrid controller. The curves at the bottom show the target brake torque values for the left and right wheel. During severe steering back a brake torque pre-control at the curve inside wheel (right wheel) is used to apply the brake pads to the brake discs to reduce pressure build up time (see Fig. 13, dotted lines).

Such a hybrid controller can easily be extended beyond the previously mentioned discrete states to cover other driving situations like e.g. slalom driving.

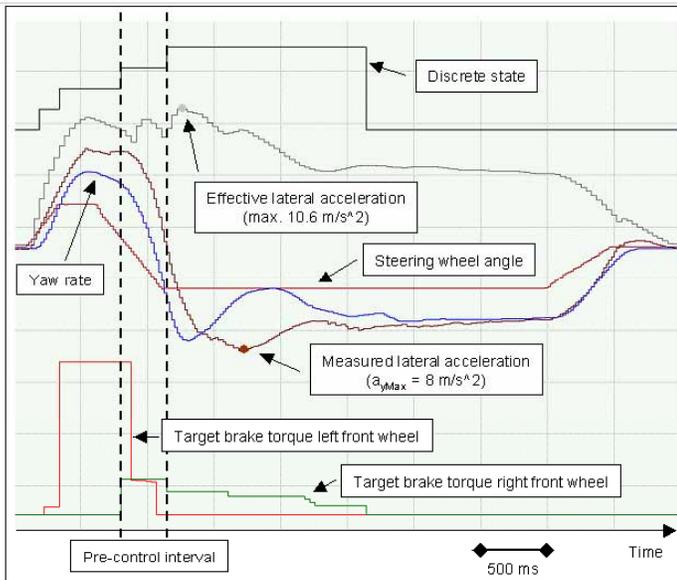


Figure 13: Example of a severe steering maneuver: NHTSA Fishhook with a sporty SUV model with ESP 8; entrance velocity $v_F=72$ km/h.

Since the major parameter to recognize rollover-critical driving situations is the measured lateral acceleration a_y relative to the center of gravity. This value plays an important role in the execution and release of roll-stabilizing interventions and in the determination of the suitable strength. However, only the measured lateral acceleration is not sufficient to clearly detect rollover-critical situations in due time and to prevent incorrect interventions at high lateral accelerations in otherwise uncritical driving situations. Beside the lateral acceleration a_y , a lead in the form of the lateral acceleration gradient, the steering angle velocity and the steering angle itself are used to calculate a so-called effective lateral acceleration. In the Fishhook example above, the effective lateral acceleration is plotted indicating the rollover propensity during this severe steering maneuver.

If the fixed release threshold dependent on the beforehand mentioned effective lateral acceleration is used to execute roll-stabilizing interventions, an improved behavior can be realized for the empty as well as fully laden vehicle with a minimized comfort impairment due to early braking interventions. For vehicles with a high variance of the center of gravity height, an adaptive rollover mitigation strategy is

designed. It uses the vehicle's mass and the estimated CoG position to adjust the threshold for brake interventions. This ensures timely interventions with the correct intensity and minimized comfort impairment.

CONCLUSION

The results of several independent studies show a consistent picture of the ESP with remarkable safety benefits and proof the positive impact. Further potential is available with functional extensions especially for SUV and light trucks concerning rollover mitigation and 4WD adaptations. The ESP with Rollover Mitigation functions helps the driver to stay on the road and to avoid tripping obstacles by a specific yaw control. It also supports the driver with an optimized lateral acceleration control to manage rollover critical on-road situations. In cooperation with four wheel drive train concepts, ESP delivers at the same time the expected safety benefits and excellent off-road and handling functionality.

REFERENCES

1. Rabe, M.; VW-Research, Germany, 5. Symposium Automatisierungs- und Assistenzsysteme für Transportmittel, Braunschweig, Germany, (17-Feb-2004).
2. Papelis, Y.E.; Brown T.; Watson G.; Holtz, D.;Pan, W.; University of Iowa, National Advanced Driving Simulator, Document ID: N04-003-PR.
3. Aga, M.; Okada, A.; Toyota, Japan, Paper No. 541, JSAE Automotive Engineering Exposition, Yokohama, May 2003.
4. Foerster: "Der Fahrzeugführer als Bindeglied zwischen Reifen, Fahrwerk und Fahrbahn", VDI-Berichte, Nr. 916 (1991).
5. Van Zanten, A. et al.: "Control Aspects of the Bosch-VDC". International Symposium on Advanced Vehicle Control AVEC '96, 1996.
6. Van Zanten, A. T.: "Bosch ESP systems: 5 years of experience". SAE 2000-01-1633, 2000.
7. Chen, B.-C.; Peng, H.: "Differential braking based rollover prevention for Sport Utility Vehicles with human-in-the-loop evaluations". Vehicle System Dynamics, Vol. 36, No. 4-5, pp. 359-389, 2001.
8. National Highway Traffic Safety Administration (NHTSA): Final Policy Statement on NCAP Rollover Resistance Rating, Consumer Information, 2003.
9. Ackermann, J.; Odenthal, D.: "Damping of vehicle roll dynamics by gain scheduled active steering". Proc. European Control Conference, Karlsruhe, Germany, 1999.
10. Sampson, D.J.M.: "Active Roll Control of Articulated Heavy Vehicles". Ph.D. thesis, Cambridge University Engineering Department, UK, 2000.
11. BMW EDC, see <http://www.bmw.co.za/Products/FIRST/Active/act-EDC.htm>
12. Brown, T. A. et al.: "Rollover Stability Control for an Automotive Vehicle". US patent No. 6,263,261 B1.

13. Branicky, M.S.: “Studies in Hybrid Systems: Modeling, Analysis, and Control”. PhD Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, USA, 1995.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ESC: Electronic Stability Control

ESP: Electronic Stability Program
SUV: Sport Utility Vehicle
LT: Light Truck
4WD: Four Wheel Drive
ABS: Anti-Lock Control
CCC: Center Coupling Control
CoG: Center of Gravity
SSF: Static Stability Factor
NHTSA: National Highway Traffic Safety Administration
RMF: Rollover Mitigation Function
HRMC: Hybrid Rollover Mitigation Controller