Influence of Driving Attributes on the Risk of Rollover and the Touchdown Conditions of a Sedan in Case of Corrective Maneuvers

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Abstract

The goal of this study was to assess the sensitivity of (corrective) driving inputs on the risk of rollover of a sedan and the resulting touchdown conditions in case of soil trip rollover crashes. The driving inputs include the initial steer that leads to the departure from the roadway, the corrective steer in an attempt to gain back the control and the initial travel speed of the vehicle. Latin hypercube sampling was used to uniformly sample various combinations of driving inputs and corresponding simulations were run using a multibody model of a sedan validated for aggressive driving maneuvers and quasi-static suspension tests. Logistic regression model was fit to predict the probability of the binary outcome of rollover with the driving input as predictor variables. The model involving interaction between the predictor variables had a better predictive capability than the main effects model. The initial travel speed and the first steer angle were the most influential in affecting the risk of rollover of the vehicle. The touchdown parameters varied depending on the peak lateral acceleration at trip and the trip location from the road. The peak lateral acceleration and trip location in turn varied depending on the driving inputs. The study established a methodology to estimate the sensitivity of the risk of rollover of a sedan and distribution of corresponding touchdown parameters to driving inputs in case of corrective maneuvers.

Keywords Driving input, Multibody, Rollover, Steering induced, Soil trip, Touchdown, Vehicle dynamics

I. INTRODUCTION

Rollover crashes accounted for about 35.5 percent of all occupant fatalities in 2008 in the United States [1] in spite of their low incidence rate of 2 percent. The National Highway Traffic Safety Administration (NHTSA) has taken measures in order to improve rollover crashworthiness of vehicles. Federal Motor Vehicle Safety Standard (FMVSS) No. 216, roof crush resistance, establishes a minimum requirement for roof strength to reduce deaths and injuries due to the crushing of the roof into the occupant compartment. FMVSS No. 226, ejection mitigation, which applies to side curtain airbags which when deployed, should prevent occupant ejection through side windows. Electronic Stability Control (ESC) helps prevent the lateral skidding and loss of control of the vehicle that can lead to rollovers. FMVSS No. 126 requires all passenger cars beginning with the 2012 model year to be equipped with ESC, which meets the standards specified by NHTSA. Sivinski has reported an estimated 67% reduction in the likelihood of vehicles equipped with ESC being involved in a rollover crash [2]. Several other researchers have come to similar conclusion regarding the effectiveness of ESC in prevention of rollover crashes. However, NHTSA estimates that 5,000 to 6,000 fatalities per year would still occur in a fleet fully equipped with ESC [3] and therefore there is a need for further reducing the fatalities resulting from rollover crashes. Padmanaban et.al. concluded from the study of 478 rollover crashes of vehicles equipped with ESC as standard equipment that the effectiveness of ESC diminishes particularly when the vehicle departs the roadway, under environmental factors such as slick road conditions, or when driver factors such as speeding, fatigue, distraction, inattention and overcorrection are present [4]. This poses an interesting question of how driving factors like speed, steering angle and steer rate would influence the risk of rollover under off-road maneuvers in the presence of unpaved road or soil. Understanding this influence could potentially lead to improvement of the ESC under off-road maneuvers or development of other active safety features like steer-by-wire control to mitigate off-road soil trip rollover crashes which constitute about 90 percent of all trip-over crashes [5].

Efforts have been made to develop controlled and repeatable dynamic rollover testing methodology which take some of the 12 kinematic states (position, speed, orientation and angular rate) of the Center of Gravity (CG) of vehicles at roof-to-ground contract (touchdown conditions) as inputs to study the interaction between the roof and the ground in a controlled dynamic fashion [6]. The choice of these test parameters (roll rate, roll angle, drop speed, travel speed at touchdown and pitch angle of the vehicle) become significant as they could affect the outcome of the test due to the chaotic nature of rollover events [7]. Drop speed is the vertical component of the global velocity vector of the vehicle at the time of touchdown. Travel speed is the resultant value of the lateral and longitudinal velocities of the vehicle. Simulation of soil trip rollover crashes provides a viable methodology to study the effect of driving factors in influencing the touchdown conditions of a vehicle at first roof-to-ground contact and thereby assess the variability of these conditions.

Existing literature was reviewed to identify representative driving scenarios and the range of driving inputs. Deutermann found that prior to a crash 61 percent of the vehicles were traveling straight in case of single vehicle rollover crashes [8]. Parenteau found that most rollovers were initiated by tripping (trip-over), where the lateral motion of the vehicle is suddenly slowed or halted [5] and that more than 90 percent of trip-over were caused by contact with the ground. Viano and Parenteau reviewed 63 National Automotive Sample System – Crashworthiness Data System (NASS-CDS) cases from 1995-1999 and reported that 90 percent of vehicles in their study departed the road on to the shoulder and unpaved area and more than 70 percent of vehicles were skidding as they departed the road [9]. Asay et al. conducted two series of steering induced soil trip rollover involving sedans and Sports Utility Vehicles (SUV) on an actual highway [10-11]. Their steering input included a first steer to deter the vehicle on to the unpaved area and a second corrective steer during which the vehicle rolled before it made back on to the paved surface. This maneuver was considered for current study as it was known to induce a rollover.

Doi et al. examined 100 volunteer (ordinary) drivers using a driving simulator under two conditions: obstacle avoidance and slippery curve control [12]. Under the obstacle avoidance maneuvers, they reported a maximum steer angle of 121 deg and steer rate of 372 deg/s. Under the slippery curve control, their reported range for maximum steer angle varied from 0-300 deg and steer rate varied from 50-800 deg/sec.

The goal of this study was to assess the influence of driving factors, such as the steer angle, steer rate and the speed of the vehicle, in influencing the risk of rollover and the touchdown conditions in case of steering induced soil trip rollover crashes involving a corrective input from the driver. Corrective maneuvers can be classified as those in which there is an active steering input from the driver after the vehicle departs the roadway in order to gain back control of the vehicle and make it back on to the road. To facilitate this study, the model of a sedan validated for aggressive driving maneuvers and quasi-static suspension tests developed by Kim et al. was used to analyze the sensitivity of risk of rollover and touchdown parameters to driving factors [13]. Multibody models of the vehicle were preferred for this study owing to their simplicity, faster computation time to run a large sensitivity analysis and their accuracy in simulating the vehicle dynamics.

The first steer maneuver in the current study could be considered to encompass driving maneuvers aimed to avoid obstacles, veering due to distraction, falling asleep or loss of control due to unknown reasons. The range of 40-200 deg was considered for the first steer angle and the range of 20-400 deg/s was considered for the first steer rate (SWR1) to encompass all the possible first steer maneuvers. For the second steer maneuver, a minimum steer angle of 50 deg was chosen to ensure that the driving maneuvers represent a corrective trajectory. The maximum steer angle possible in most of the steering systems is around 1.5 complete rotations, which amounts to 540 deg. The second steer rate range considered for this simulation was 50-700 deg/sec. They were chosen to be similar to the range observed from the volunteer study in case of slippery curve control maneuver [12].

II. METHODS

Model Description

Kim et al. developed multibody models in ADAMS CAR (MSC Corporation) of a sedan (Figure 1) and a pickup truck. The model responses were validated in quasi-static response of the suspension (bounce, roll and lateral compliance) [14] and dynamic response of the vehicle under aggressive maneuvers including fish hook, J turn, sinusoidal steer and circular steer at different speeds [13].

The sedan model developed by Kim et.al. (Figure 1) was used in the current study to analyze the sensitivity of the risk of rollover and touchdown parameters to driving inputs like the steer angle, steer rate and the travel speed of the vehicle. The sedan had a MacPherson front and a multi-link rear suspension. The geometry of the suspension was modeled with the aid of accurate 3D measurement of joint locations and directions with the aid of FARO arm (FARO Technologies Ltd).

An analytical model of the tire based on magic formula tire formulation had been implemented to better capture the road tire interaction under dynamic conditions [15]. Tire model parameters were obtained in tire tests that varied sideslip angle, camber angle and normal force.

Soil tire interaction

A semi-empirical model to capture the tire-soil interaction under off-road maneuvers [16] has been implemented to execute the dynamic simulation of off-road maneuvers. The model calculates the tire sinkage into the soil based on Bekker's method assuming a rigid wheel [17]. It also allows the computation of the tire forces caused by terrain deformation in longitudinal and lateral direction based on curve fits of soil data combined with soil mechanics theories to capture soil compaction, soil shear deformation, and soil passive failure that are associated with off-road driving. Soil parameters measured from Michigan sandy loam soil were used in the current study [18]. This soil formulation was chosen for the current study as it produced moderate soil ploughing force compared to other prevalent soil types like clayey soil, dry sand or lean clay.

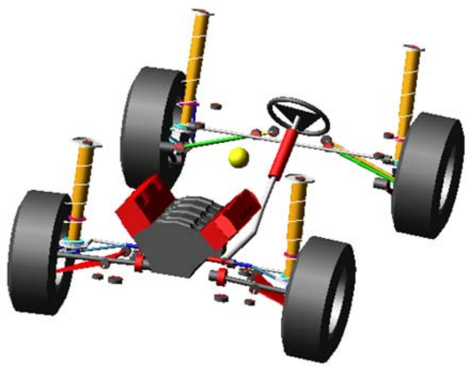


Fig. 1. Multi body model of a sedan

Road Model

A two-lane highway was modeled following the roadway design guidelines (Figure 2) [19]. The coefficient of friction of the paved area (lanes and shoulder) was set to 0.95 and the coefficient of friction of the unpaved area (shoulder wedge, recovery area and median) were set to be 0.6 [18]. A slope of 6 to 1 was used for the shoulder wedge, recovery area and the median. The soil model was engaged during the simulations when the wheel center of each individual tire stepped into the unpaved area.

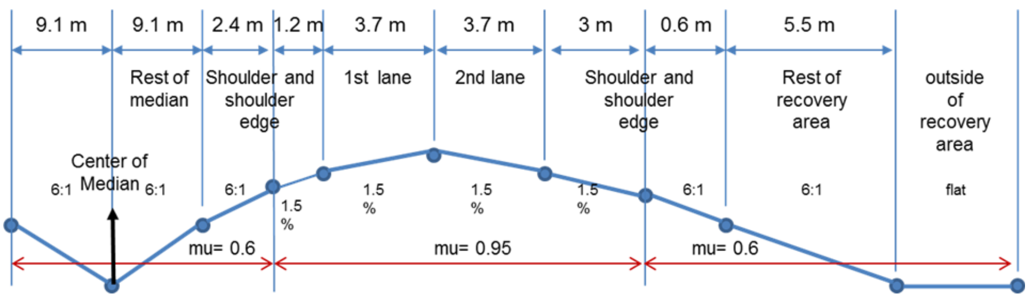


Fig. 2. Two lane highway schematic

Driving Maneuvers

The pre-event behavior of the vehicle was chosen to be travelling on a straight road. For simplicity, the vehicle was chosen to be travelling in the first lane (left) in the two-lane highway. Corrective steering input from the driver was characterized by a left steer (SWA1) at a constant rate (SWR1) was applied to the vehicle so that it leaves the roadway on to the unpaved terrain. Once the vehicle enters the off road area (shoulder and the rest of the median) a right steer (SWA2) at a constant rate (SWR2) and then a hold was applied to make it back on to the roadway (Figure 3). The total duration of the maneuver was 6 seconds. ESC was not modeled during the current study.

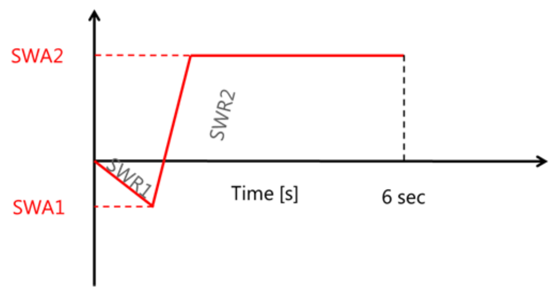


Fig. 3. An example steering input

Driving input

A Latin hypercube sampling methodology was used to construct plausible collections of driving input parameters to run the simulations from the limits on each variable (Table 1). A set of 5000 independent combinations of the driver inputs were generated for the current study

Table 1
Driver input for the simulations

Driver input parameter	Lower bound	Upper bound
1st steering wheel angle (SWA1) [deg]	40	200
1st steering wheel rate (SWR1) [deg/s]	20	400
2nd steering wheel angle (SWA2) [deg]	50	540
2nd steering wheel rate (SWR2) [deg/s]	50	700
Initial Speed (V0)[km/h]	80	145

Exclusion of simulations

It was noted during the simulations that a spurious high contact force was being induced at the wheels in the model for some simulations as the vehicle crossed the center of median (Figure 2) due to the sudden difference in the slopes of the road at the center. This was occurring due to the limitation in the modeling capabilities of road to tire contact in ADAMS. The median was acting like a curb in some cases and, therefore, all the simulations that crossed the median were omitted in the current study.

Roll Initiation and Touchdown conditions.

Roll initiation was detected in a simulation when the contact force (reaction force) between the ground/road and tires became zero. To identify the touchdown conditions, a set of markers were placed on the exterior geometry of the vehicle which is rigidly attached to its CG. The markers were placed to cover all possible roof to ground contact locations in a discrete fashion. The kinematics of each marker was tracked throughout the entire duration of simulation. In case of a rollover, the simulation was stopped when any of the discretized markers touched the ground level and the kinematics of the CG of the vehicle at this last step was considered as the touchdown conditions.

Analysis

Rollover outcome is a binary variable with the outcome being a roll or no roll. Typically logistic regression is used to model binary outcomes of the dependent variables. In the current study, two multivariate linear logistic regression models were used to evaluate whether the risk of rollover is sensitive to the explanatory variables (driving inputs) i.e. first steer angle (SWA1), first steer rate (SWR1), second steer angle (SWA2), second steer rate (SWR2), initial speed of the vehicle (V0). Whether the vehicle rolled over was indicated with a binary variable, which served as the dependent variable in these regression analyses. The first model (M1) included all the main effects of the explanatory variables (SWA1, SWR1, SWA2, SWR2 and V0). The second model (M2) included the second order interaction terms of V0 with the rest of the parameters (V0 x SWA and V0 x SWR) and

steering angle with the steering rate for each maneuver (SWA x SWR) along with the main effects. A third model M2* was constructed based on the elimination of statistically insignificant variables from the model M2.
The logit of the probability of rollover, $P(R)$ was modeled as a linear function of the value of the predictors, x_i:

$$P(R) = \frac{1}{1 + e^{-q}}$$

Where

$$q = \alpha + \sum_i \beta_i x_i$$

q is the logit function, $\alpha$is the intercept, $x_i$are the model predictors, and β_i are the coefficients associated with each predictor.

The relative significance of each predictor variable for each model was assessed using the P value corresponding to the Z score of the variable and the P value corresponding to the Chi-square value of each variable from the Analysis of Variance (ANOVA) analysis. Kruskal's Gamma and the area under the receiver operator characteristic curve (ROC) were used to analyze the relative predictive capabilities of the three models.

Analysis of touchdown parameters

The variation of each touchdown parameter with each driving input was studied to identify the parameters that are influenced by driving inputs. To understand the cause of variation in touchdown parameters, some intermediate states of the vehicle like the peak lateral deceleration, the sideslip angle of the vehicle at trip and the lateral distance of tripping location from the road have been investigated. Peak lateral acceleration refers to the maximum value of the lateral acceleration of the CG of the vehicle before it trips. The sideslip angle at trip refers to the angle between the ground velocity of the vehicle and its heading direction at the time of trip. The lateral distance of trip is the distance travelled by the vehicle lateral to the road until the point of trip. The variation of the first quartile, median and third quartile values of each parameter over the range of driving inputs was investigated in the current study. In order to evaluate the quartile and median values of touchdown parameters the range of driving inputs were binned into 150 bins of equal size. There was an overlap ensured between each bins to smooth abrupt variations. For each binned region the first quartile, median and third quartile values of touchdown parameters were evaluated and the values have been associated with the mid-point of the bin. A small enough bin size was ensure to capture the variations in the values of the parameters ensuring continuity in the values in between different bins due to the overlap.

Analysis of interactions between driving inputs

To study the interaction between SWA1 x V0, SWA1 x SWR1 and, SWA2 x SWR2 the 2-D domain (of the variables under study) has been divided into 150x150 equal areas with ensured overlap between each smaller area. All the simulations were binned into the appropriate area and the probability of rollover was calculated for each of the bins to understand the local variation of the risk of rollover over the 2-D domain. Using the coefficients obtained from the logistic regression, the variation of probability with the variables SWA1 x V0 and SWA1 x SWR1 was compared against the binned simulation data to draw inferences on the nature of interaction terms. A modified model incorporating higher order (4^{th} order) interactions was tested if it could better represent the nature of interaction among some of the covariates.

III. RESULTS

Because of the first steering input, the model left the roadway to the left side on to the shoulder and median area. Depending on the steering input, the vehicle either crossed the center of median or was in between the center of median and the roadway at the end of the first maneuver. On further application of corrective steering input (SWA2 and SWR2) to the right, the vehicle either made it back on to the roadway or rolled over during the corrective maneuver. All the simulations in which the model crossed the center of median during any phase of maneuver were omitted from the current study. Out of 5000 simulations performed, 2686 could be used for the current analysis and 234 of those cases sustained a rollover due to the ploughing force applied on to the tires as the vehicle was maneuvering off-road.

Roll Probability

In the main effects model (M1) the covariate SWR2 was not found to be significant at *P*=0.05 level (Table 2). In the model with interactions (M2) the covariates V0 and the interaction terms except SWA1 x SWR1 and SWA1xV0 were not found to be significant at *P*=0.05 level. SWA1 and V0 were the top two influential variables in the prediction of roll probability in case of M1 based on the Z scores (Table 2). Model M2 shows that the interaction terms SWA1xSWR1 and SWA1 x V0 were the most influential in prediction of roll probability based on the Z scores.

Table 2

Model coefficient estimates and S.E. for model M1 and model M2

Predictor	Model M1				Model M2			
	Estimate	S.E.	Wald Z	*P* (>|Z|)	Estimate	S.E.	Wald Z	*P* (>|Z|)
			-					
Intercept	-12.641	0.766	16.500	<0.0001	-9.736	3.258	-2.990	0.003
SWA1	0.031	0.003	12.370	<0.0001	-0.039	0.018	-2.240	0.025
SWR1	-0.004	0.001	-3.860	<0.0001	-0.016	0.008	-2.020	0.044
SWA2	0.003	0.001	4.870	<0.0001	0.010	0.005	2.140	0.033
SWR2	0.001	0.001	1.310	0.191	0.009	0.005	1.990	0.047
V0	0.204	0.017	11.720	<0.0001	0.152	0.089	1.720	0.085
SWA1 x SWR1					0.100	0.000	3.640	0.000
SWA2 x SWR2					0.000	0.000	-1.170	0.241
SWA1 x V0					0.150	0.001	2.940	0.003
SWR1 x V0					0.010	0.000	0.460	0.648
SWA2 x V0					-0.020	0.000	-1.200	0.232
SWR2 x V0					-0.020	0.000	-1.650	0.099

The generalized Wald test between model M1and M2 showed that the difference in the predictive ability of the model M2 with the exclusion of interaction terms is statistically significant with *P*=1E-5. The model M2* (Table 4) was construed by the exclusion of the covariate SWR2 and the interaction terms SWA2 x SWR2, SWR2 x V0, and SWR2 x V0. A Wald test in between model M2 and M2* showed that the exclusion of these variables does not affect the predictive ability of the model with P=0.25. The most important consideration in either the inclusion of interaction terms (M2) into the main effects model (M1) or dropping some of the interactions and main effects to form the reduced model (M2*) is that the model is able to better discriminate a rollover from a non-rollover case. The indicators of discrimination improve from the model M1 to M2 whereas remain unchanged from M2 to M2* (Table 5). It has to be noted that the coefficient estimates of the predictor variables have been scaled taking into account the relative magnitudes of each predictor variables for easy comparison (V0 (m/s) scaled by 10 and SWA (deg/s) x SWR (deg/s) scaled by 0.001 and SWA (deg/s)/SWR (deg/s) x V0 (m/s) scaled by 0.01) (Table 2 & Table 4). The Chi-square statistic from the ANOVA of models M1 and M2 showed that the predictor variables SWA1 and V0 still remain the most influential predictors of the risk of rollover amongst both models and SWR1 is statistically insignificant (Table 3).

Table 3

ANOVA Wald chi-square statistics for Model M1 and Model M2

Predictor	Model M1			Model M2		
	Chi-square	DOF	*P* (>Chi)	Chi-square	DOF	*P* (>Chi)
SWA1	152.91	1	<.0001	154.47	3	<.0001
SWR1	14.94	1	<.0001	29.16	3	<.0001
SWA2	23.68	1	<.0001	26.75	3	<.0001
SWR2	1.71	1	0.191	5.10	3	0.16
V0	137.31	1	<.0001	144.76	5	<.0001
SWA1 x SWR1				13.26	1	<0.001

SWA2 x SWR2	1.37	1	0.24
SWA1 x V0	8.62	1	0.00
SWR1 x V0	0.21	1	0.65
SWA2 x V0	1.43	1	0.23
SWR2 x V0	2.73	1	0.10

Table 4

Model coefficient estimates and ANOVA statistics for model M2*

Predictor	Model M2*					
	Estimate	S.E.	CI	Chi-square	DOF	*P*(>Chi)
Intercept	-4.659	1.8477	-8.2817:-1.0355			
SWA1	-0.036	0.0152	-0.0656:-0.0059	188.78	3	<.0001
SWR1	-0.012	0.0025	-0.0171:-0.0073	30.5	2	<.0001
SWA2	0.003	0.0006	0.0018:0.0041	24.69	1	<.0001
V0	0.030	0.0516	-0.071:0.1315	150.68	2	<.0001
SWA1 x SWR1	0.100	0.0000	0:0.0001	12.18	1	5.00E-04
SWA1 x V0	0.150	0.0004	0.0007:0.0023	12.43	1	4.00E-04

Table 5

Predictive performance of the models

	model M1	model M2	model M2*
Kruskal's Gamma	0.854	0.870	0.870
Area under ROC	0.710	0.742	0.743

Analysis of interaction of driving inputs

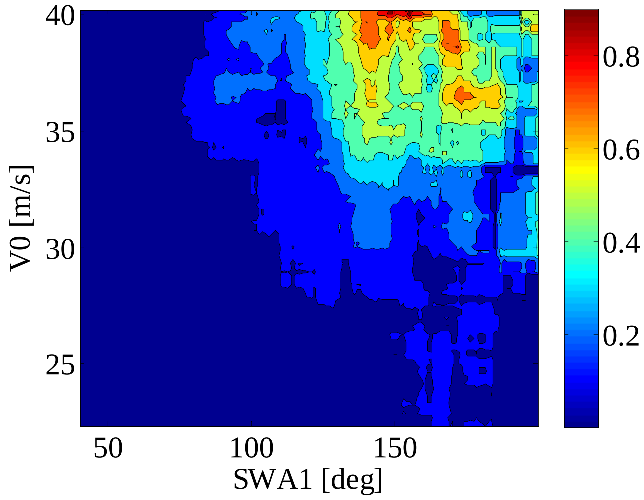
The effect of the interaction between driving inputs (SWA1 x V0, SWA1 x SWR1 and SWA2 x SWR2) have been shown with the aid of contour plots (Figure 4- Figure 6). The roll probability has been mapped with color in case of each plot with the color dark blue represents the least value of the probability of rollover and the color red representing the highest value of the probability of rollover encountered over a range of driving inputs. A color bar has been depicted in each figure describing the actual range of roll probability in each case.

In case of the interaction between the first steer angle and the initial speed of the vehicle the models M2* and M2 ** depicted similar interaction when compared to the simulation result where the risk of rollover increased with both speed and steer angle (Figure 4 a, Figure 5 a and Figure 6 a).

Although the risk of rollover generally increased with SWA1, the effect of the first steer rate (SWR1) was not the same at every first steer angle (SWA1). At small steer angle (SWA1), the risk was higher for small steer rate (SWR1). At intermediate steer angle, the risk was higher for intermediate rate. At larger steer angle, the risk was higher at large steer rate (Figure 4 b). The interaction effect from the reduced model M2 * could not fully depict the nature of interaction shown from the simulation results (Figure 5 b). A modified model M2** incorporating the higher order interaction of SWA1 and SWR1 (fourth order) was able to better depict the interaction (Figure 6 b).

$$M2^{**} = M2^{*} + (SWA1 * SWR1)^2$$

The model predicted that SWR2 had little or no effect in explaining the variation in the outcome of the risk of rollover, however the analysis of the simulation data (Figure 4) showed that there is a minimum SWR2 below which there were no rollover and in general the risk of rollover increased with SWR2.



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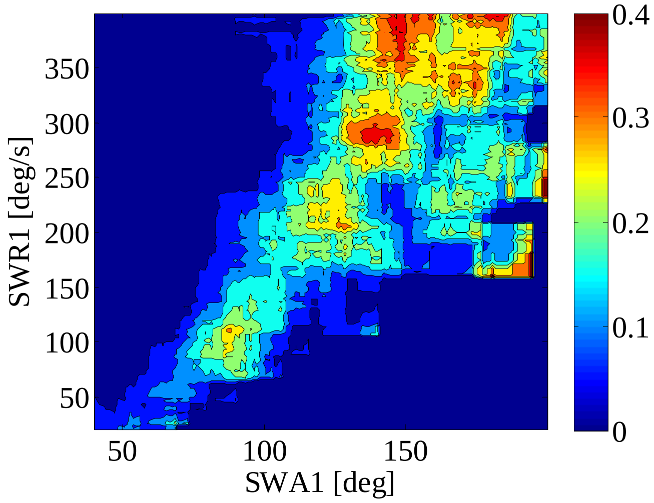

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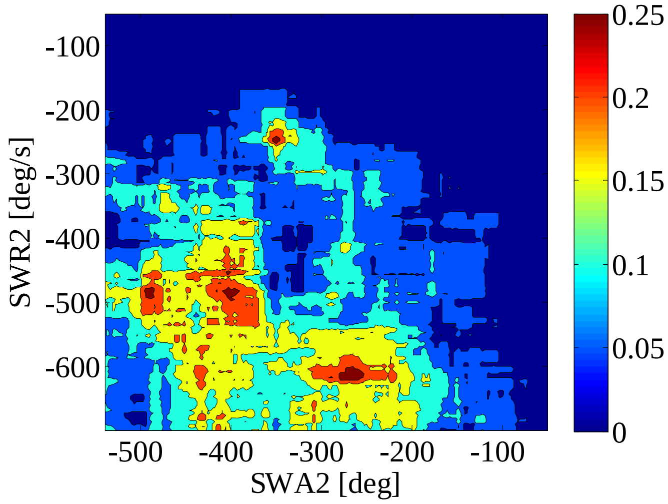
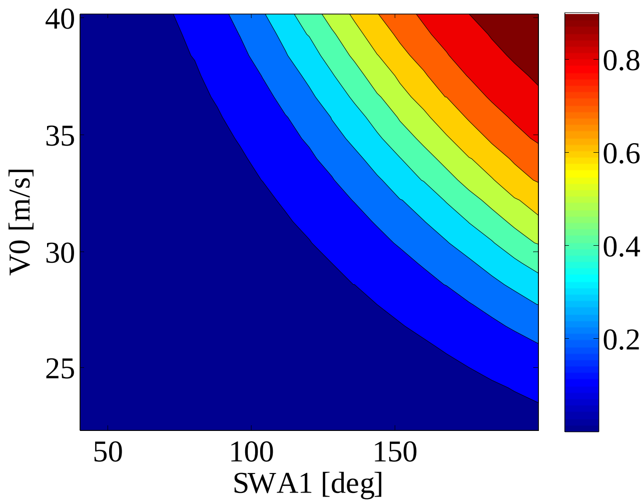


4 c

Fig. 4 (a, b, c). Effect of interaction on rollover risk from simulation data



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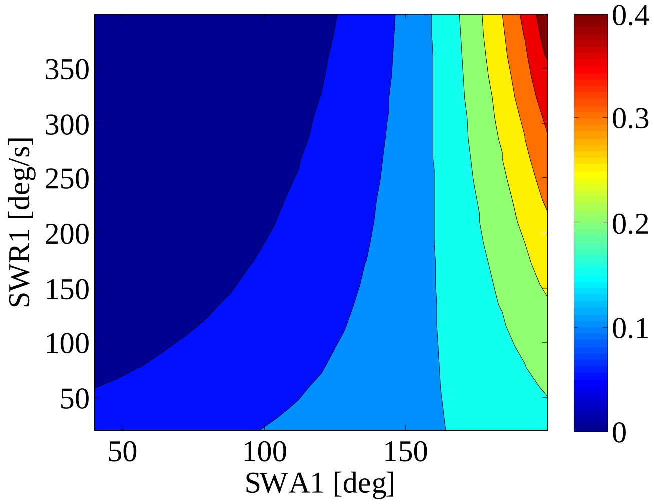

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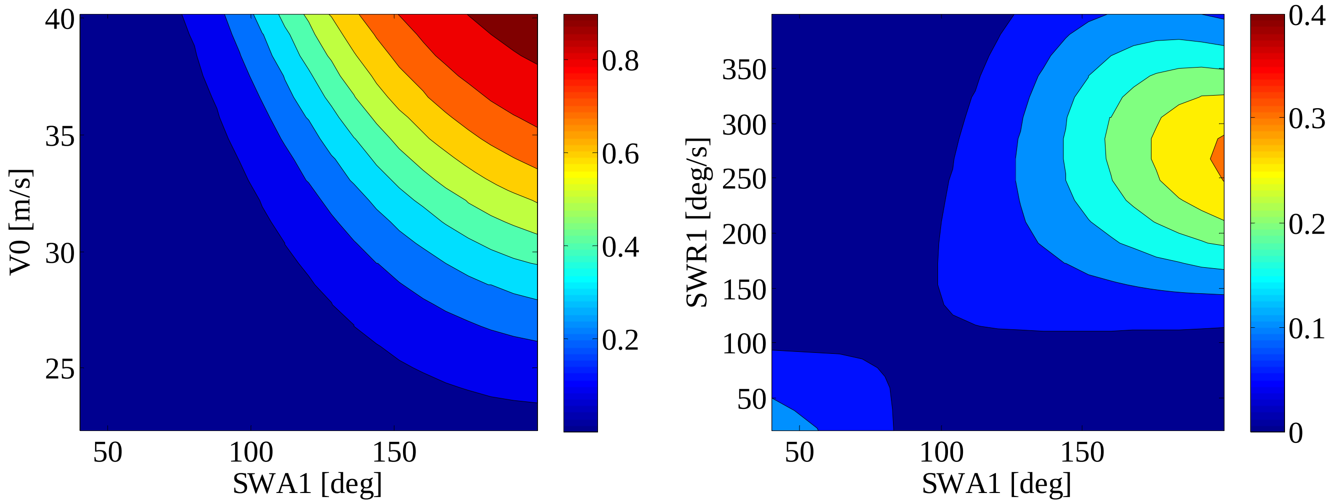
Fig. 5 (a, b). Effect of interaction on rollover risk in the reduced model M2*



6 a 6 b

Fig. 6 (a, b). Effect of higher order interaction on rollover risk in the reduced model M2**

$$M2^{**} = M2^{*} + (SWA1 * SWR1)^2$$

Touchdown sensitivity

There was considerable spread in the touchdown parameters with the standard deviation of the parameters varying from 20-50 percent of their mean values (Table 6). The travel speed at touchdown increased with increase in V0 (Figure 8). The median value of drop speed increased initially with SWA2 but maintained itself with further increase of SWA2 (Figure 9). The roll rate also increased initially with V0 but maintained its value with further increase of V0. There was also a slight drop of roll rate observed with increase in SWA2 (Figure 10). The roll angle followed a similar trend to roll rate but the drop in roll angle with respect to SWA2 was more significant compared to roll rate (Figure 11).

The slip angle at trip remained unaffected by the various steering inputs (Figure 12). The peak lateral deceleration increased (decreased) with V0 (SWA2) and maintained itself with further increase of V0 (SWA2) (Figure 13). The lateral distance travelled until the point of trip increased with V0, SWA1, SWA2 and SWR2 (Figure 14). There was a strong correlation observed between the roll rate of the vehicle at touchdown and the peak lateral acceleration experienced by the vehicle at the time of the trip (Figure 15).

Table 6

Mean and SD of touchdown parameters

Touchdown parameters	Mean	SD	% SD
Travel speed	13.6	6.1	44.8%
Drop speed	2.6	0.9	34.6%
Roll rate	247.3	51.8	20.9%
Roll angle	98.3	19.5	19.8%
Pitch angle	-11.7	5.2	44.4%

IV. Discussion

Roll Probability

1) Main Effects

This study has shown that the risk of rollover in case of corrective maneuver is strongly dependent on the first steer angle (SWA1) and the initial speed of the vehicle (V0) which can be seen from their higher chi square values (Table 2-Table 4). The first steer causes the vehicle to develop a sideslip where its heading direction differs from the travel direction (Figure 7). The cornering stiffness saturates with slip-angle (of tires) and excessive slip-angle of vehicle and rear axle generally indicates an over-steer condition which may lead to loss of control. At such side slip angles any further corrective steer increases the chance of loss of control of the vehicle. The larger the first steer angle, the larger the amount of sideslip produced during the corrective maneuver. The increase in initial speed of the vehicle further increases the sideslip, which ultimately results in a higher ploughing force being applied to the vehicle [16].

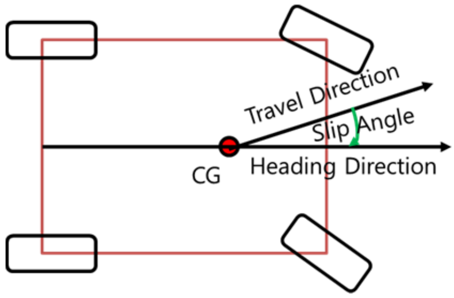


Fig 7 Slip angle

It was interesting to note that the main effects model (M1) showed that the second steer rate (SWR2) did not have a significant effect on the roll outcome of the vehicle. However, the simulation results (Figure 4 c) showed that there is minimum SWR2 below which there were no rollovers and the risk of rollover generally increased with second steer rate. But it can be considered that it was the least influential variable in effecting the risk of rollover from the lower Chi square values (Table 3) or lower Z score (Table 2). This is because once we cross a certain threshold of second steer rate (SWR2), it only affected how fast the vehicle reaches the required sideslip condition to produce enough lateral deceleration to initiate the roll. SWR2 has been dropped from the model M2* as it wasn't influencing at p=0.05 level and it has to be considered as one of the limitations of using a logistic regression model.

2) Interaction Terms

It has to be noted that although the risk of rollover generally increased with SWA1, the effect of the first steer rate (SWR1) was not same for every first steer angle (SWA1). At lower steer angles higher rate meant that the vehicle travelled for less time off road in soil and did not lose control (Figure 4 b). This is particularly significant at lower angles because the amount of lateral motion of vehicle is limited owing to lower steer angles. At higher steer angles (SWA1), the risk of roll over increased with steer rate (SWR1) which is expected. At intermediate steer angles (SWA1), risk was the maximum at intermediate steer rates. This is because at intermediate steer angles, the vehicle still travelled for a lesser time off-road at higher rates. But the slip produced at intermediate rates were higher than the slip produced at lower rates for intermediate steer angles therefore there was an optimum steer rate at which the risk was maximum.

The interaction of SWA1 and V0 had a compounding affect where increase of both the values lead to an increase in the risk of rollover (Figure 4 a). The interaction between the initial speed and any other variables were not so significant because by the time of the corrective maneuver, a proportion of the speed of the vehicle would have dropped and the initial speed could no longer influence the effect of other variables. Therefore the interaction terms SWR1 x V0, SWA2 x V0 and, SWR2 x V0 have been dropped in model M2*

*3) Reduced model M2**

As the relative significance of main effect variable SWR2 and the interaction terms SWA2 x SWR2, SWR1 x V0, SWA2 x V0 and, SWR2 x V0 was low compared to other predictor variables, it can be seen that they did not affect the predictive capability of the reduced model M2* when they were dropped. This can be seen from the very similar values of Kruskal's Gamma and Area under ROC between models M2 and M2* (Table 5).

As a general rule of thumb models that produce ROC [20] within the range of 0.5-0.6 are considered to have little or no utility as a discriminating tool, 0.6-0.7 poor utility, 0.7-0.8 moderate utility, 0.8-0.9 good utility, and 0.9-1 excellent utility [21]. Therefore the current reduced model M2* has a moderate ability in discriminating the rollover crash. This can be also seen from the wide confidence interval for the most significant variables of the model M2* (Table 4). The wide confidence interval is also an indicator of the chaotic nature of rollover crashes where a slight variation in the initial conditions could potentially change the outcome of the scenario.

All the simulations that crossed the median were neglected from the study and this could lead to some discontinuity in the model because there could have been potentially some cases, which could have ended up rolling over under corrective inputs after crossing the median. Owing to the large confidence interval of the logistic model and moderate area under ROC value a nonlinear regression model like random forest could be implemented to improve the predictive capability of the model.

Touchdown sensitivity

The variation in peak lateral deceleration (Figure 13) at trip and the lateral distance of the trip location of the vehicle from the road were useful in understanding the variation in some of the touchdown parameters. The Peak value of the lateral acceleration decreased with increase in SWA2. After analysis of simulation data, it was observed that here was a higher tendency of the right wheels of the vehicle to lift off the ground at the start of the corrective maneuver. This increased the dynamic load on the left wheels of the vehicle, increasing the penetration of wheel into the soil leading to higher ploughing force. The value of the peak lateral acceleration could be divided into two levels a high value of greater than 1.5 g and a low value of less than 1.5 g and this grouping was attributed to the liftoff of wheels during the second maneuver increasing the ploughing force on the tire.

The lateral distance (from the road) travelled by the vehicle until the trip location increased with VO, SWA1 and SWR1 (Figure 14). The effect of initial speed V0 is very intuitive in increasing the lateral distance. More steer angle implied that the vehicle deviated more laterally due to the steer. From the sensitivity of roll probability, it was seen that higher first steer rate were associated with higher first steer angle for the vehicles, which rolled, and therefore they covered more distance laterally. The lateral distance at touchdown also increased with SWA2 and SWR2. This is because the vehicle lost tracking more easily under higher second steer angles and rates and therefore ended up covering more distance laterally.

The travel speed (Figure 8) of the vehicle at touchdown increased with initial speed (V0) since the peak lateral deceleration did not vary with the speed the vehicle had a higher travel speed after trip. The median value of the drop speed (Figure 9) increased initially with SWA2 and this could be related to the trip location, which was closer to shoulder in case of lower SWA2. This is because the vehicle would have less airborne time when it is closer to the shoulder because of the slope of the shoulder and the shape of the vehicle.

There was a linear dependence between roll rate and peak lateral acceleration (Figure 15). The lateral acceleration is dictated by the soil force being applied on to the vehicle, which in turn affects the angular momentum being imparted to the vehicle due to the soil force. Higher soil force generated higher moments, which increased the roll rate of the vehicle.

The roll angle (Figure 11) followed the trend of roll rate (Figure 10) but it should be noted that the trip location could play a role in influencing the roll angle at touchdown due to increasing slope of the off road terrain with lateral distance.

Effect of soil

The above distribution of touchdown parameters is a function of soil properties. However, it is expected that the relative sensitivity of the touchdown parameters to driving inputs would remain the same. It is necessary to investigate the effect of soil to confirm the hypothesis.

Vehicle Type and safety systems

The above sensitivity of the risk of rollover and touchdown conditions is only valid for the particular type of vehicle (sedan) considered for this study. It is expected that different class of vehicles like a sports utility vehicle (SUV), pickup truck, minivan etc. would show different trends owing to their differences in inertial properties, wheel base and vertical CG height affecting the static stability factor (SSF), different suspension properties, different tires, steer ratio etc. The proposed methodology could be used to study the effectiveness of safety systems like ESC, Anti-lock braking etc. over an entire range of driving maneuvers.

V. CONCLUSIONS

The above study has shown that the driving attributes influence the risk of rollover of a sedan with the initial speed of the vehicle (V0), the first steer angle (SWA1)and its interaction with first steer rate (SWR1) being the most influential ones. The logistic regression model was able to capture some of the interactions between the predictive variables however owing to the chaotic nature of rollover it was not enough to completely describe it. The touchdown parameters were also found to be sensitive to the driving parameters with the drop speed, travel speed and the pitch angle being the most influenced touchdown parameters.

VI. Acknowledgement

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VIII. APPENDIX

Sensitivity of touchdown parameters

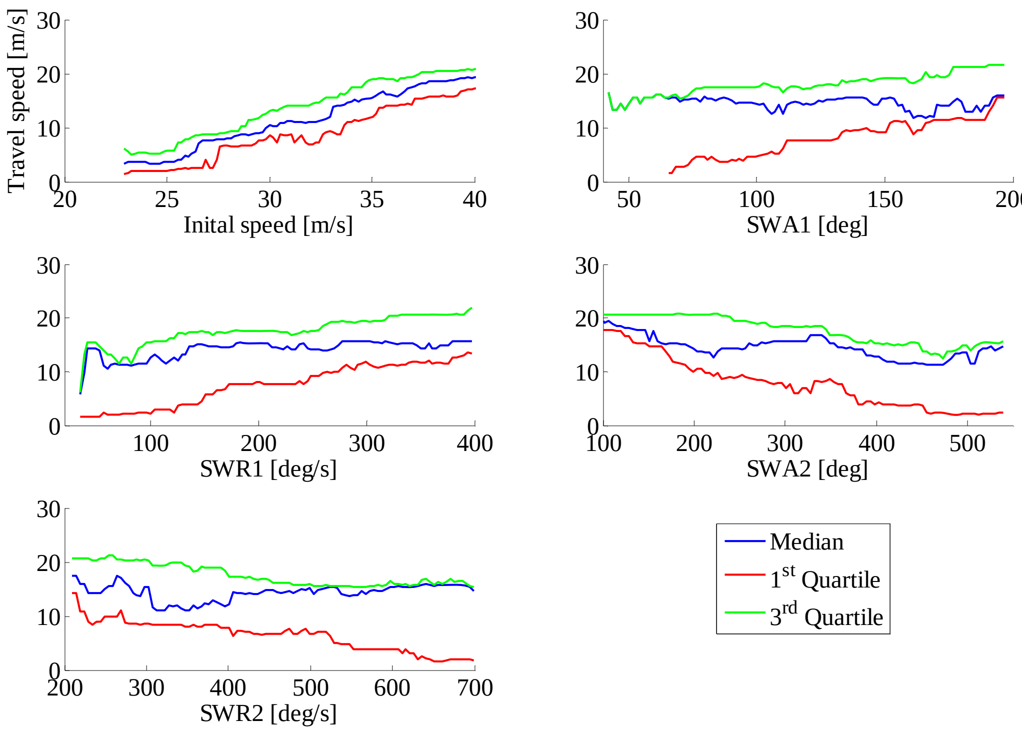

Fig. 8. Variation of travel speed with driving input

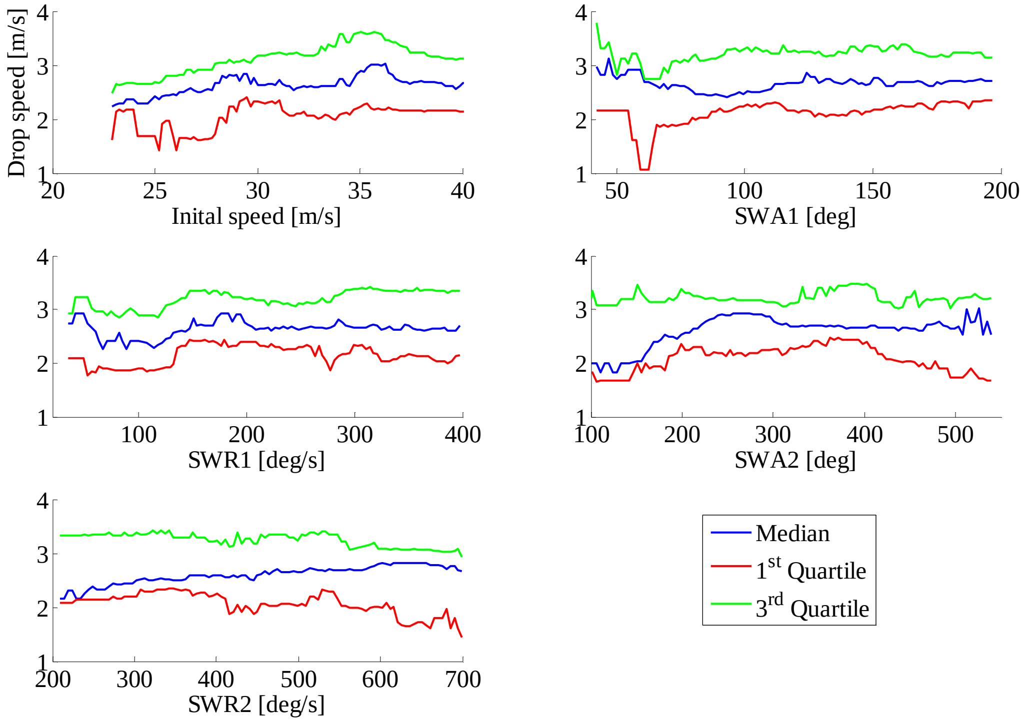

Fig. 9. Variation of drop speed with driving input

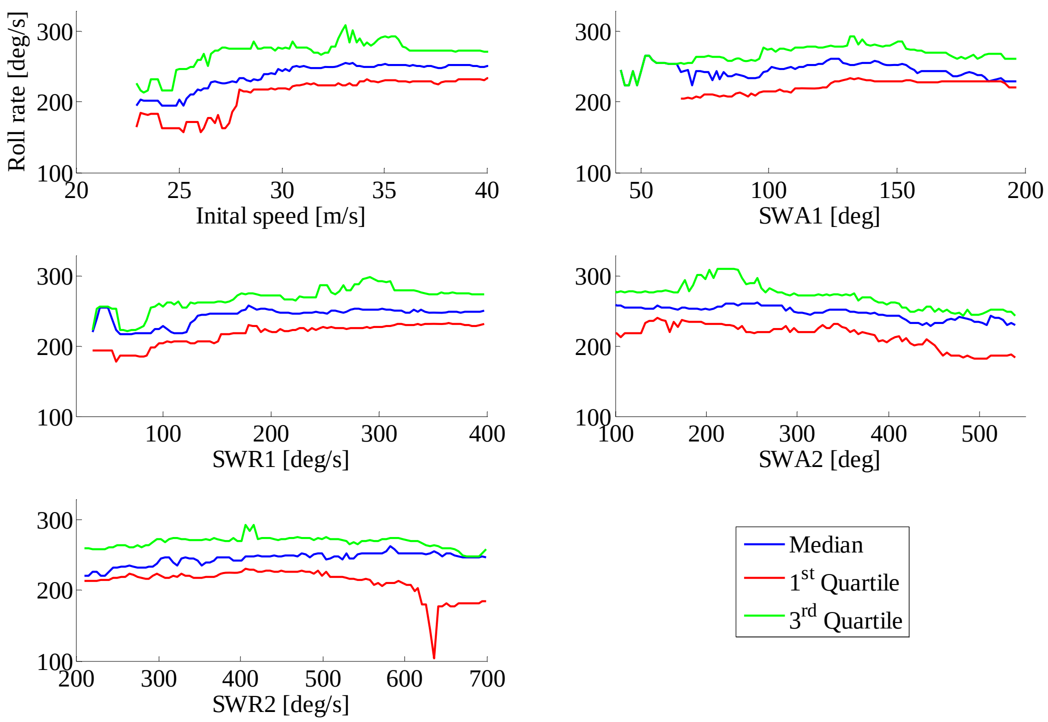

Fig. 10. Variation of roll rate with driving input

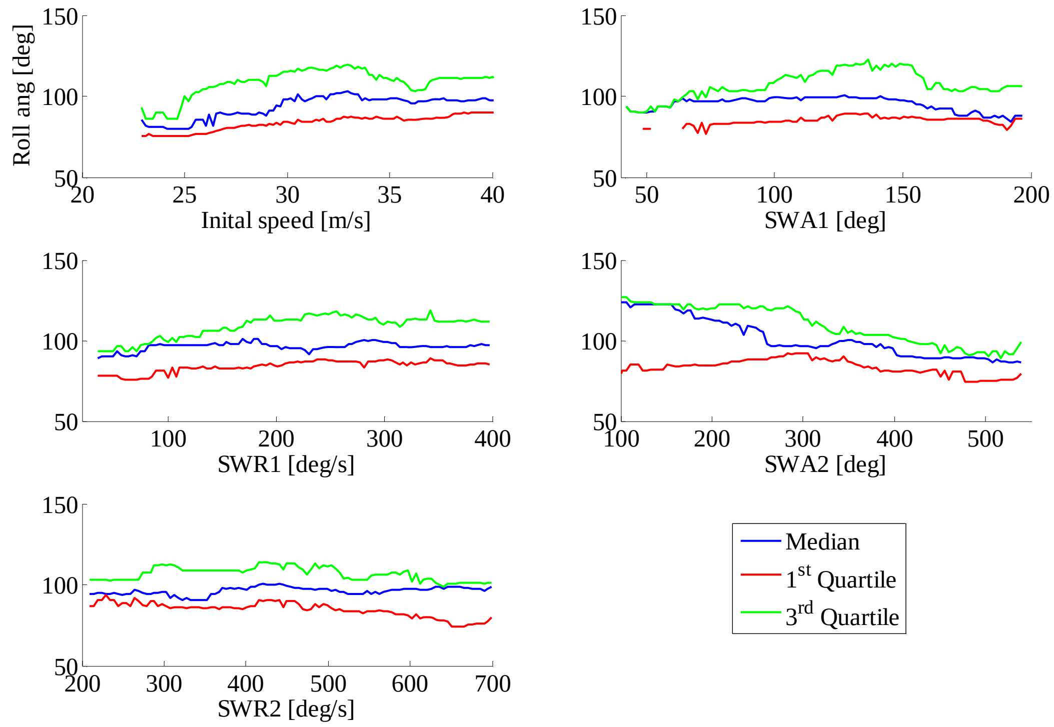

Fig. 11. Variation of roll angle with driving input

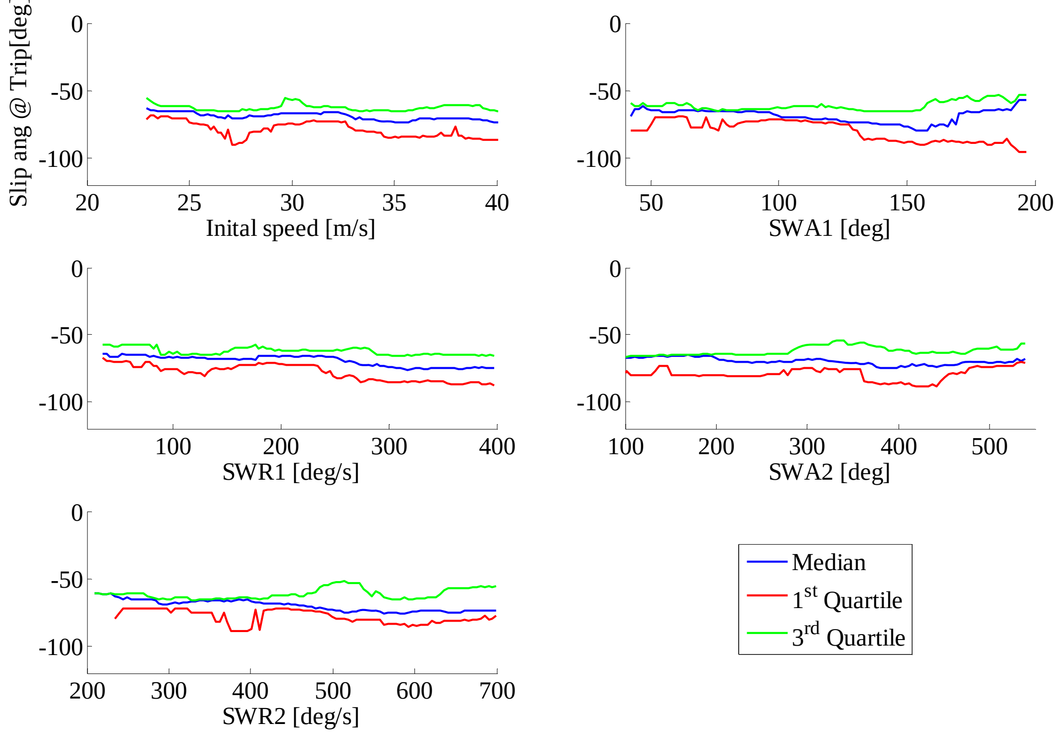

Fig. 12. Variation of side slip angle at trip with driving input

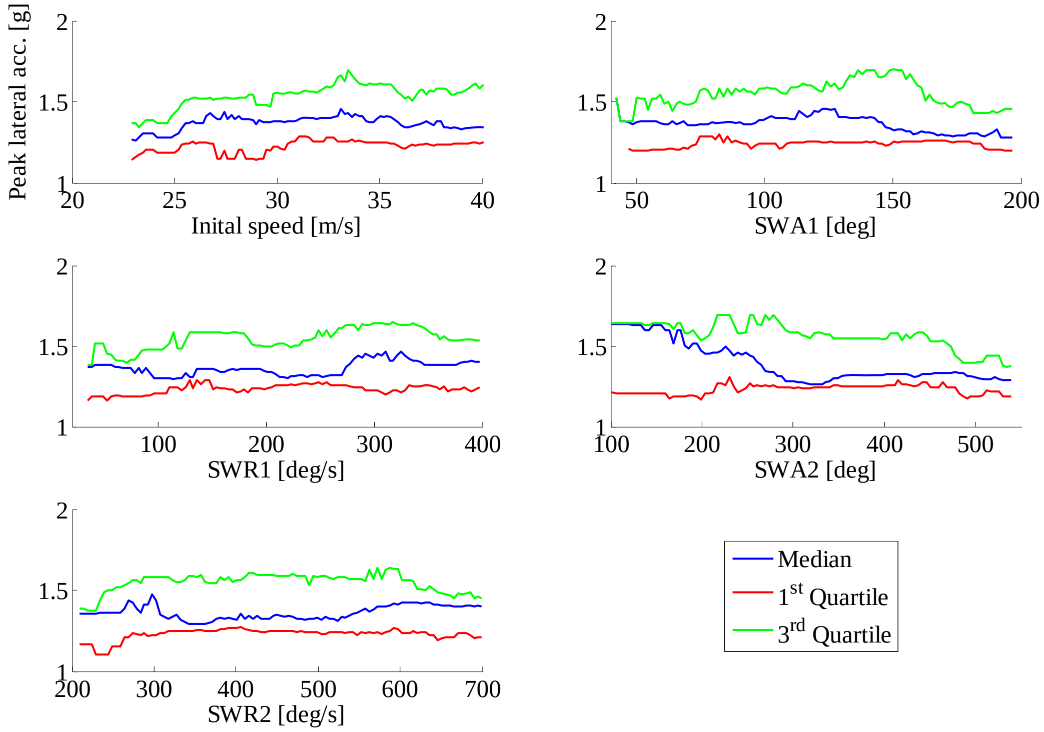

Fig. 13. Variation of peak lateral acceleration with driving input

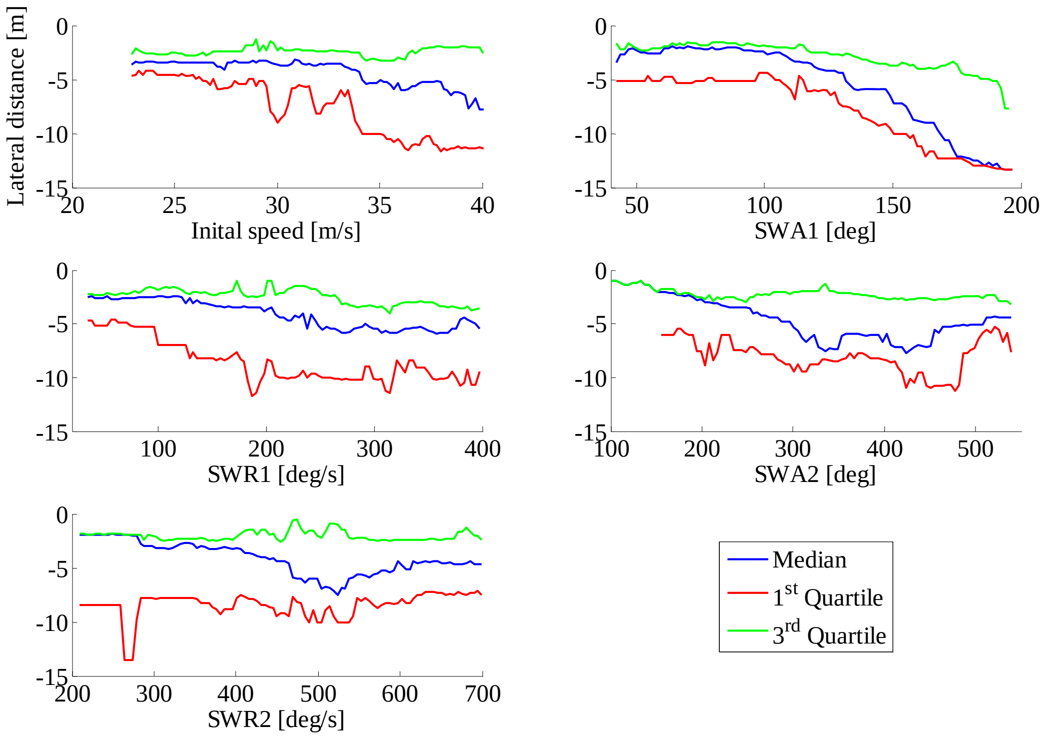

Fig. 14. Variation of lateral distance at trip with driving input

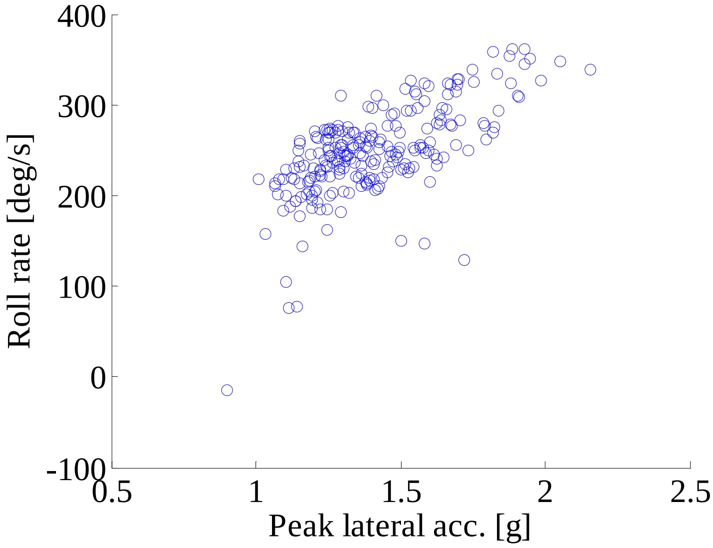

Fig. 15. Scatter plot of roll rate vs. peak lateral acceleration