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Effect of Shoulder on Safety of Highways in Horizontal Curves Using Vehicle Dynamic Modeling Considering Yaw Rate

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ABSTRACT: Skidding in horizontal curves is a common type of accident that endangers passenger safety and may happen due to various reasons. Investigating the co-relations between Vehicle dynamic parameters and road shoulder type by taking yaw rate changes, the human factor (speed and encroachment angle), and road geometry (width, material, and slope of shoulder and roadway) via vehicle dynamic simulation helps to realize the skidding mechanism on horizontal curves caused by the shoulders. The importance of this study reveals by considering that similar studies have not probed the relations between vehicle dynamic and shoulder parameters based on observing the danger of skidding. The simulation process in this study is conducted via the vehicle dynamic simulation software Carsim and Trucksim which can evaluate the stability of the vehicle in various driving conditions. By conducting 324 scenarios generated by the simulation software, several models are achieved based on the relation between parameters affecting vehicle yaw rate for Sedan, SUV, and Truck types of vehicles. Scenarios are generated by considering unwanted road departures in horizontal curves in all types of vehicles with various speeds and placements of outer tires on different types of shoulders. As the results of the simulated scenarios demonstrate, the average yaw rate of a Truck is 6.41 to 19.65 percent higher than the SUV and Sedan types, respectively. Even though the average amount of yaw rate for Sedan against SUV and Truck is greater by 6.7% and 20%, respectively. Also, the simulation results show that when the outer tires are on a gravel shoulder and the inner ones are on the roadway in horizontal curves, the amount of yaw rate for Sedan, SUV, and Truck would be 1.06, 0.76, and 0.66 percent, respectively, which are lower than the cases in which the gravel shoulder is replaced with an asphalt one. Furthermore, Results indicate that shoulders with various widths, cross slopes, and materials, influence aspects of highway safety-related to vehicle yaw rate significantly. This influence depends on the dynamic and geometric features of each type of vehicle.

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1- Introduction

One of the critical components of highways is horizontal curves in which skidding and road departure lead to high mortality rates. Highway safety can be significantly enhanced with a well-designed shoulder by utilizing appropriate width, cross slope, and materials. Road shoulders are designed and constructed with various widths and materials such as gravel, asphalt, and concrete, depending on local conditions. Studies on shoulder width and other parameters have been conducted by some researchers; Using data collected from Minnesota and Washington states, Karlaftis and Tarko have studied the effects of lane width, shoulder, crash proneness on road margins, and traffic volume on traffic collisions. As the result of this study which is figured out through negative binomial regression, ADT, lane width, shoulder width, and crash proneness in the road margins have the most significant role in the frequency of collisions in straight routes, while the ADT is the prominent cause of crashes at intersections [1]. The width of the road shoulder depends on its function and varies from 0.6m in minor rural roads to 3.6m in major highways according to AASHTO [2]. According to research conducted by Vaa et al. (2012), rural roads with shoulders have 5 to 10 percent fewer crash rates in comparison with the roads without a shoulder [3]. A study on the effects of road shoulder on highway safety via vehicle dynamic simulation conducted by Abdi et al. (2015) showed that a 2% reduction in Roll rate can be achieved by increasing shoulder width from 1 to 2.6m [4]. For evaluating low-cost safety strategies as part of its strategic highway safety effort the FHWA organized a pooled fund study of 26 States. Using data from Pennsylvania and Washington, a matched case-control analysis was conducted to determine the safety effectiveness of lane and shoulder width configurations for total paved widths from 7.92 to 10.97m. A complement analysis of narrow pavement

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widths7.32) m total paved width) on rural undivided two-lane roads in Pennsylvania shows a strong correlation between traffic volume and lane and shoulder configuration. Increased traffic volumes result in a nonlinear increase of the CMFs. In addition, each lane and shoulder configuration has a specific rate of increase. It is beneficial to provide more narrow lanes with wider shoulders at low AADTs (less than 1,000 vehicles per day) for narrow pavement widths, however, the configuration with 3.66m lanes and no shoulders appears to be most beneficial for large AADTs (greater than 1,000 vehicles per day) [5]. Concerning f_y -the effects of vehicle dynamic parameters and shoulder parameters on yaw-rate- this research conduct a vehicle dynamic simulation to enhance road safety by lowering vehicle skidding potential. Next, it is tried to describe some of the studies conducted by researchers further. Lv et al. (2004) showed that an increase in vibrations can be observed in slip angle and yaw rate as speed increases. Such responses become more frequent when steering, which complicates the task of vehicle stability control. Although research has not directly investigated the effects of speed change on vehicle control, the operation is still significant.

Existing research has employed nominal cornering stiffness to design yaw moment controllers to evaluate linear lateral dynamic models. Although yaw moments depend on lateral forces acting on tires, such forces highly depend on vertical tire load as well as road conditions. Therefore, tire corner stiffness cannot be determined definitely due to the high sensitivity of vehicle motion and road conditions. Road conditions are important when reaching conclusions about yaw moments and should be considered in future research [6]. In another paper, the stability evaluation parameter (for run-off-road vehicles) is defined as a parameter handling the evaluation of vehicle stability in different stages of returning to a normal and proper manner. Vehicle yaw rate and sideslip are recorded in every test, which is then used to calculate the stability parameter. When the vehicle is being steered back to the passing lane, the amount of yaw rate is minimum while vehicle sideslip is higher, which means that the driver has lost control or side skidding has occurred. Safe amounts of yaw rate and sideslip depend on tire pavement, friction, and the amount of vehicle skidding [7]. In addition, to prevent vehicle skidding, we can control yaw moment, which is considered in severe maneuvers according to driver requirements for the safe control of the vehicle. The required vehicle yaw rate is typically provided by an appropriate distribution of lateral and longitudinal forces exerted on the left and right sides of the rear and front axle of the vehicle. Today, the required yaw rate has been obtained and is being utilized in anti-lock braking systems (ABS), vehicle dynamics control, electronic stability control, and creating left-right moments by different active devices on the vehicle. According to research, using installable hardware on vehicles and the development of new methods for yaw moment control can highly influence the forces acting on tires and vehicle dynamics [8]. In 2019 a study was done to evaluate. In this study for US Roads, it was determined that compared to no-casualty accidents, casualty accidents are more sensitive to traffic volume, outside shoulder width, pavement condition, and median width but less sensitive to the average vertical grade. For the relatively lowest-class roads (State Roads), it was determined that, compared to no-casualty accidents, casualty accidents are more sensitive to the traffic volume, lane width, outside shoulder width, and pavement condition. Compared to the relatively lower-class highways, accidents at higher-class highways are more sensitive to: changes in traffic volume, average vertical grade, median width, inside shoulder width, and the pavement condition (no-casualty accidents only); but less sensitive to changes in lane width, pavement condition (casualty accidents only), and the outside shoulder width [9]. Moomen et al. conducted a study to predict injury severity and crash frequency in a downgrade in Wyoming. This study analyzed the contributory geometric factors of truck crashes on downgrades by estimating three crash prediction negative binomial models. These models took into account the injury severity of the crashes. The results indicate that downgrade length, shoulder width, horizontal curve length, number of lanes, number of access points, and truck traffic on the highway all impact truck-related crashes and injury frequencies on downgrades in Wyoming. The results of this study will be helpful to future downgrade road design policy aimed at reducing downgrade truck related crashes [10].

As it is presented plenty of research has been conducted in the field of safety and geometrical design but none of them has considered the effect of driver’s behavior condition and joint road shoulder design parameters such as the slope of shoulder, shoulder surface material, and shoulder width. Considering road geometry and driver behavior in the simulation process, two modes are presented for roadway departures: 1) a vehicle runs out of the road while the outer tires are on the gravel shoulder and the inner ones are on the roadway, 2) a vehicle runs out of the road while the outer tires are on the asphalt shoulder and the inner ones are on the roadway. This research utilizes dynamic simulation to investigate the effects of road shoulder on safety enhancement, considering yaw rate changes for vehicles exposed to unwanted roadway departures. The innovation of this study is to investigate the effects of road shoulder parameters on vehicle skidding based on measuring yaw rate. Moreover, regression models are being presented to be utilized in shoulder design by taking into account the characteristics of local predominant vehicles and preliminary road parameters such as design speed. The models can be used also for the safety evaluation of constructed road shoulders. In the following, the methodology of the study is explained and after that input parameters and considered scenarios are investigated. As the next step, the results are scrutinized and statistic modeling is performed and results are indicated.

2- Methodology and Mathematical Foundations of Research

The point mass model, which views the vehicle as a point, is used to identify forces and derive various design formulas in the AASHTO Green Book. Although the model can identify the forces acting on the center of gravity for various curves, grades, cross slopes, and design speeds, it has some

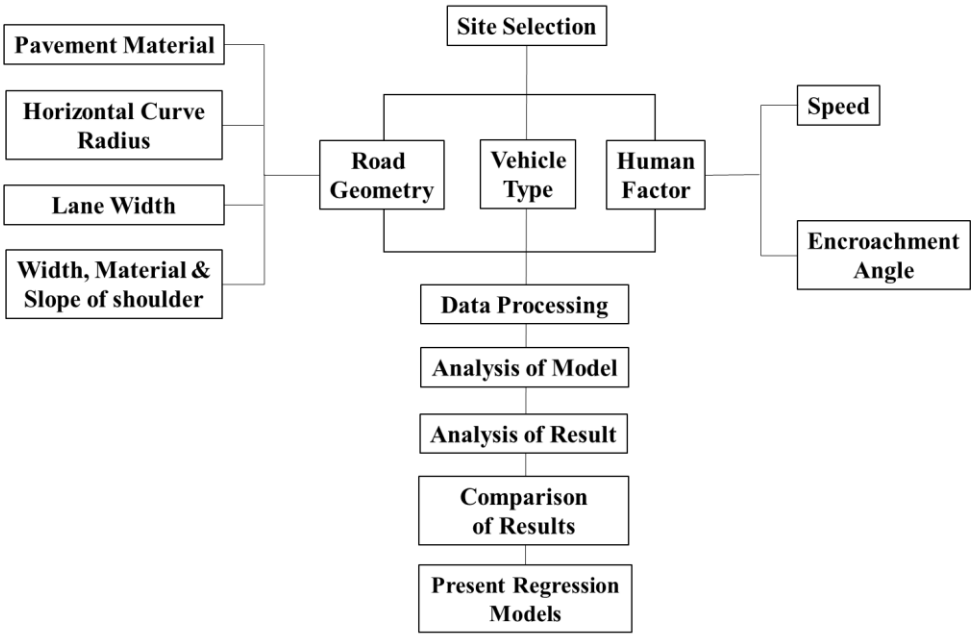

Fig. 1. Research flowchart.

shortcomings such as problems in the safety evaluation of the forces acting on the vehicle. In addition, the model neglects the angle between the road surface and the horizontal and vertical axes of the vehicle [11]. Considering such shortcomings as well as recent advances in technology, vehicle dynamic simulation software has been used (regarding vehicle three-dimensional simulation) to evaluate vehicle motion safety. Carsim and Trucksim simulation software was employed by this study due to variations in vehicle types and the necessity of considering dynamic features for the safety evaluation of vehicle motion. Several well-known vehicle manufacturing companies such as BMW and Ford as well as the authors of the NCHRP[1]report 774 have used Carsim and Trucksim for various vehicle simulating purposes. Validation of the results can be deducted from the software validation which is inferred from the comparison done between the field studies and simulations of the Trucksim software. One of these studies is the study of Qu et al., which shows the validity and reliability of the software [12]. This research evaluates the effects of vehicle dynamic parameters and highway geometry, especially highway shoulder, on the yaw rate of vehicles that have run off the road with different encroachment angles in rural highways. In this research, simulation scenarios are generated by varying the amounts of curve radius, shoulder width, design speed, roadway encroachment angle, and shoulder cross slope. Vehicle motion is simulated before the curve, in the curve, and at the moment of departure. The vehicle yaw rate is obtained in various locations using output data from the simulation software. Briefly, simulation of the vehicle motion is used as the research methodology. In this simulation, the vehicle enters the horizontal curve with a certain speed then skids so the outer tiers rotate on the road shoulder. In this situation, the driver tries to recover the vehicle and turn back to the road. Here the effect of vehicle type, vehicle speed, vehicle deviation, recovery status, and shoulder type (width, material, and lateral slope) on the yaw rate parameter is evaluated in different scenarios. The assumptions used as software input are discussed in the following sections. A summary of this paper methodology has shown in Fig. 1.

2- 1- Driver Behavior

This research aims to simulate a condition in which the vehicle runs off the road with different encroachment angles from the centerline. In this study, driver behavior is indicated in case of the vehicle runs off in horizontal curves, encroachment angle, and vehicle speed. The selected speeds are 80, 100, and 120 km/h, which are common speed limits on highways. Probable encroachment angles are assessed by valid references and determined to be 7.5 [13], 15, and 25 degrees [14]. The process of road departure begins when maximum lateral acceleration is exerted on the vehicle.

2- 2- Vehicle Type

This study includes three types of vehicles in its simulation process, namely Trucks, SUVs, and Sedans. These are the types of vehicles used for simulation in the NCHRP report 774 [15]. Some of the geometric characteristics of these

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[1] National Cooperative Highway Research Program

Table 1. Vehicle parameters.

Vehicle Type	Weight (kg)	Width (m)	Length (m)	Front axle to CG distance (m)	Height of gravity center (m)
SEDAN (E-class)	1653	1.880	4.250	1.402	0.590
SUV (E-class)	1592	1.875	4.220	1.180	0.719
TRUCK	4455	2.438	5.000	1.110	1.175

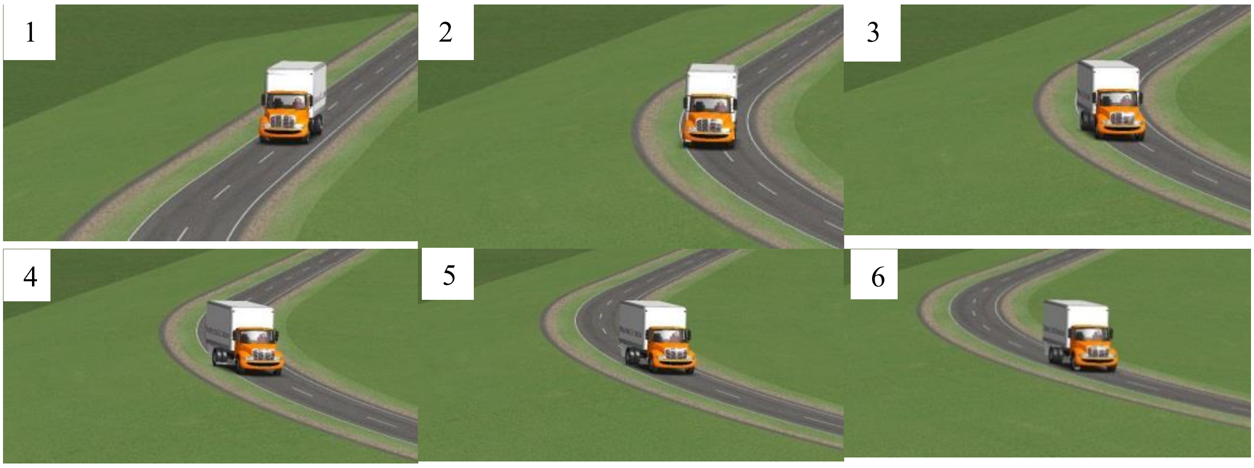


Fig. 2. Curve departure simulation and placement of the outer tires on the gravel shoulder in a horizontal curve.

vehicles are presented in Table 1.

2- 3- Road specifications

The road is one of the most important parameters in this study, which includes roadway and shoulder. Since this simulation only investigates the outer lane of a two-lane road in a horizontal curve, the width of the roadway is considered to be 3.6 meters. The purpose of considering the change of the shoulder slope was to investigate the critical state in the stability of vehicles that perverted from the road. According to AASHTO, the absolute difference value of the slope of the shoulder and roadway should not exceed 8%. Therefore, the critical points are considered. The superelevation amount is determined to be 6%, which is common in highways. Two asphalt and gravel materials are selected for road shoulder with the cross slope of -2% in contrast with the roadway cross slope of 6%. Shoulder width is selected to be 1.2, 1.8, and 2.4 m which are values recommended by the AASHTO Green Book. Concerning the maximum roadway superelevation and selected design speeds for simulation, 252, 437, and 756m were determined as minimum horizontal curve radii with design speeds of 80, 100, and 120 km/h, respectively [2].

2- 4- Pavement Conditions

Pavement conditions are defined by considering maximum surface-tire side friction, pavement materials (asphalt, gravel, or concrete), and weather conditions (dry, rainy, or snowy). In this study, the pavement surface is supposed to be dry so the maximum side friction factor for an asphalt pavement (asphalt roadway and shoulder) is selected to be 0.9 according to Ghandour et al. research16]]. Also, the value of this factor is assumed to be 1 according to Mak et al.'s research [15].

2- 5- Vehicle Movement Scenarios in Highways

Various amounts of speed, shoulder characteristics (material, width, and cross slope), vehicle types, and driver behaviors, form 324 simulation scenarios. Meanwhile, tire placement is simulated in two different ways. Scenarios are based on tire-pavement friction to be equal for all tires on a horizontal curve and the effect of friction on vehicle yaw rate. Two modes of tire placement are described in what follows.

The first: Inner tires are on the horizontal curve on the asphalt roadway and the outer tires are on the gravel shoulder. (Fig. 2 shows the vehicle movement simulation in this mode.)

Number of scenarios in the first mode: 3 vehicle types

Table 2. Parameters used in the simulation.

Parameter	Number of type	Name	Symbol
		80	
Speed(km/h)	3	100	V
		120	
		7.5	
Encroachment angel (Degree)	3	15	EN.A
		25	
Shoulder slope	2	-2%	
		6%	Sh-Slope
		1.2	
Shoulder width (m)	3	1.8	
		2.4	Width
Shoulder surface	2	Gravel	Gravel
		Asphalt	Asphalt
		Sedan	Sedan
Vehicle	3	SUV	SUV
		Truck	Truck

* 3 speeds * 3 shoulder widths * 3 encroachment angles* 2 shoulder cross slopes = 162 scenarios

The second: Inner tires are on the horizontal curve on the asphalt roadway and the outer tires are on the asphalt shoulder.

Number of scenarios in the second mode: 3 vehicle types * 3 speeds * 3 shoulder widths * 3 encroachment angles * 2 shoulder cross slopes = 162 scenarios

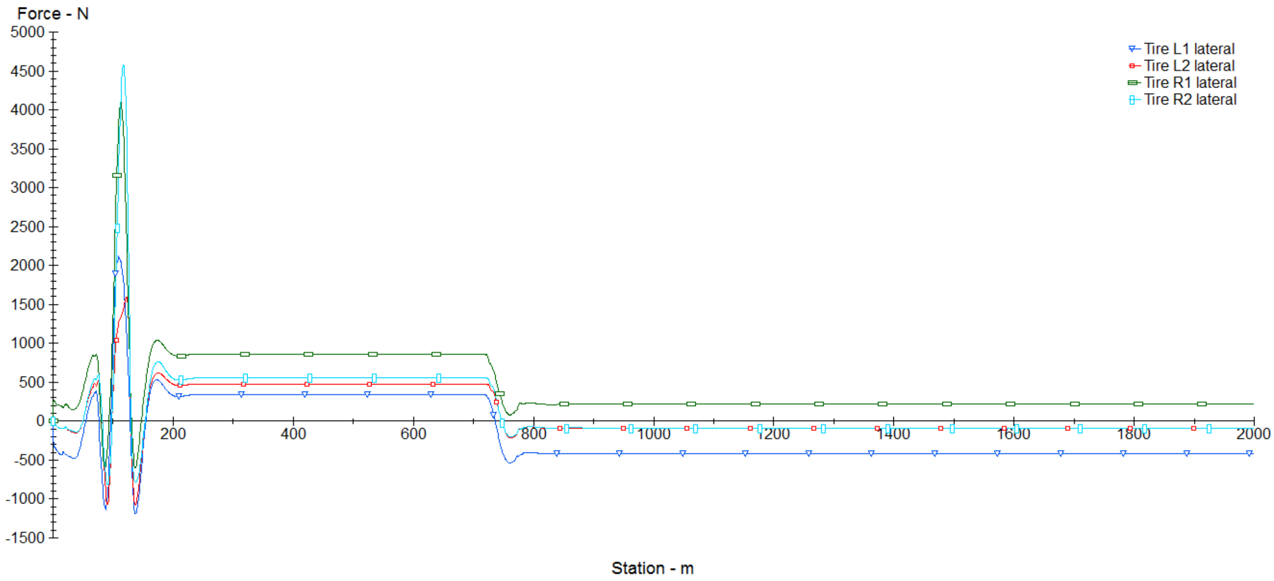
For recording yaw rate amount, at first maximum lateral force on the specific station was recorded. Then on the yaw rate chart, the relevant point with the recorded station is the desired point. The yaw rate is the most vital vehicle variable that needs to be known by a road vehicle lateral dynamics control system. These controllers also use the vehicle sideslip angle which is very expensive to measure with the presently available optical sensors. So, observers (also called estimators) are used to estimate vehicle side slip from other available sensor data. The yaw rate is measured using yaw rate gyros in the form of MEMS sensors or larger electromechanical units or by a combination of accelerometers [17]. The end of Table 2 shows all the parameters used in scenarios which were explained above in section 1 to section 7. A number of types mean the number of different values which are considered for each independent variable in Table 2. For instance, three values are considered for the vehicle speed (80, 100 and 120 Km/h).

3- Results and Discussion

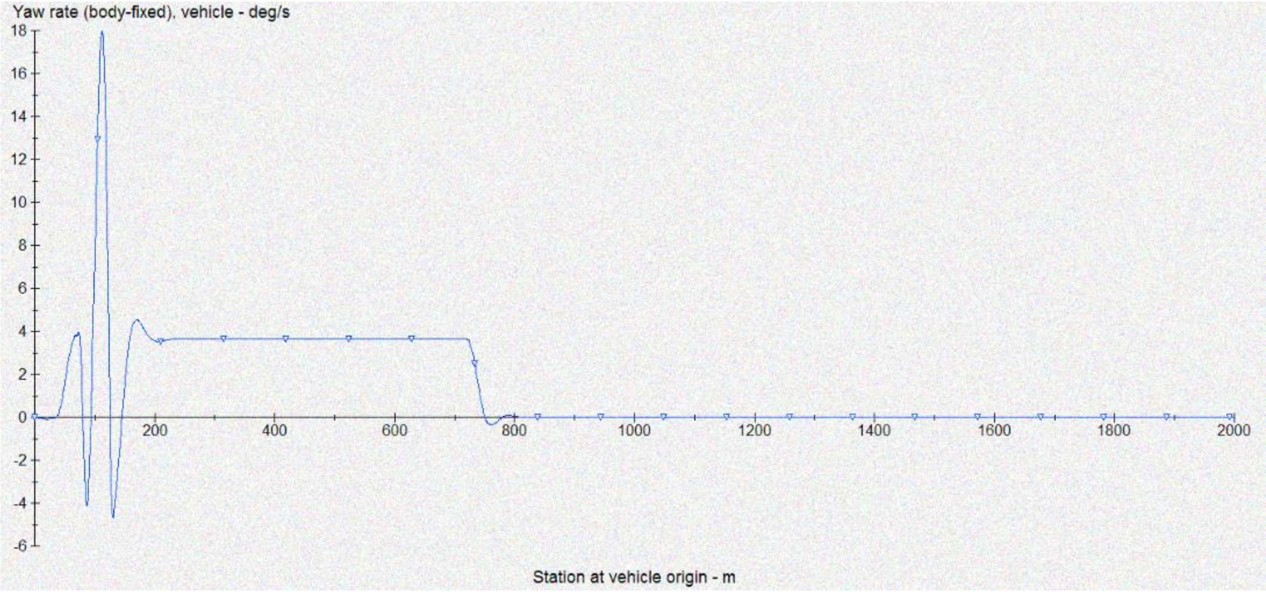
The point mass model views the vehicle as a point. All external forces act on the center of gravity, where the whole mass of the vehicle is located. However, the three-dimensional model used by the vehicle dynamics simulation software takes the distribution and the types of created forces on the tires into account. Output data is obtained from the curves created by the simulation software, which helps to determine the maximum acting lateral force location. Yaw rate values are then recorded at this location. Fig. 3 shows that as the vehicle runs out of the road, greater force is applied to the vehicle in such a way that the behind right tier of the vehicle bears the greatest force. After steering and recovery, the forces applied to the vehicle are then reduced. Fig. 3 shows the output curves of the vehicle dynamic simulation software for SUVs versus location (from the beginning location of the simulation).

Analysis of forces exerted on the vehicle (especially on trucks) shows that in addition to the lateral, vertical, and longitudinal forces, a moment acts on the vehicle as well, which is due to the weight and geometric characteristics of the vehicle. Therefore, we can derive valuable conclusions by analyzing this moment. The moment, known as the yaw moment, is one of the pivotal reasons why the rear tires of the vehicle skid around the front axle, especially at high speeds. Fig. 4 illustrates the forces and moments acting on the vehicle, in which yaw moment is determined by the direction exerted on the vehicle (Risk of a yaw rate based on the skidding of the vehicle that makes rollover).

The following chart evaluates curves related to vehicle yaw rate versus shoulder width changes (the outer tires of vehicles that unwantedly leave the road to be placed on the shoulder in a horizontal curve). In this research, yaw rate values for all 324 scenarios are derived and analyzed. Figs.



(a) The curve of the lateral forces acting on SUVs vs. location in the simulated path



(b) Curve of the SUV yaw rate vs. location in the simulated path

Fig. 3. Output data of the simulation software.

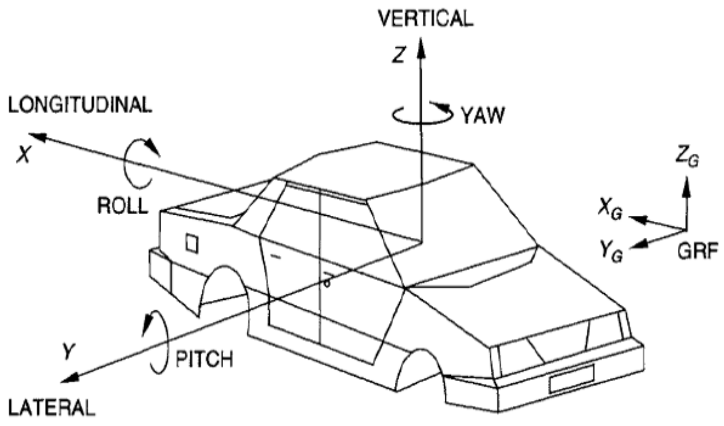
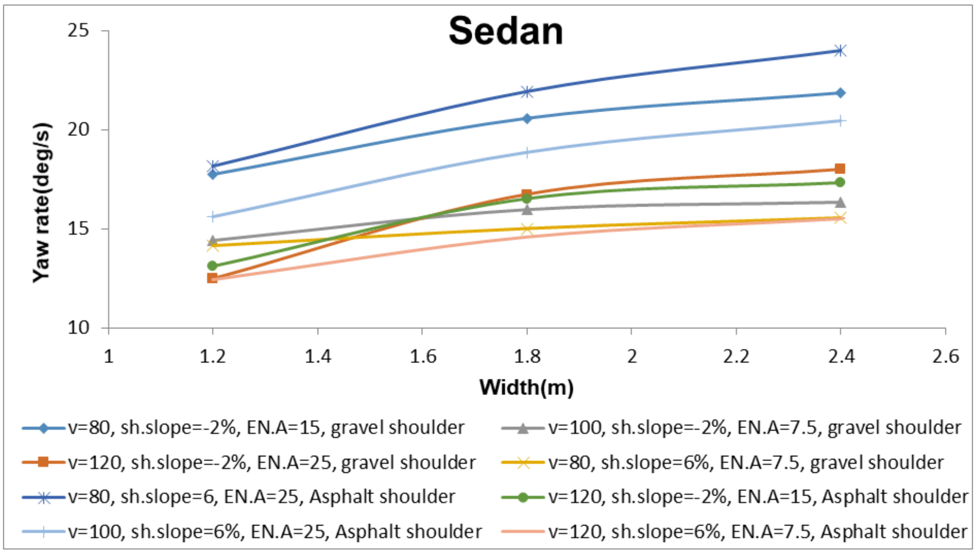


Fig. 4. Forces and moments acting on a vehicle [18].



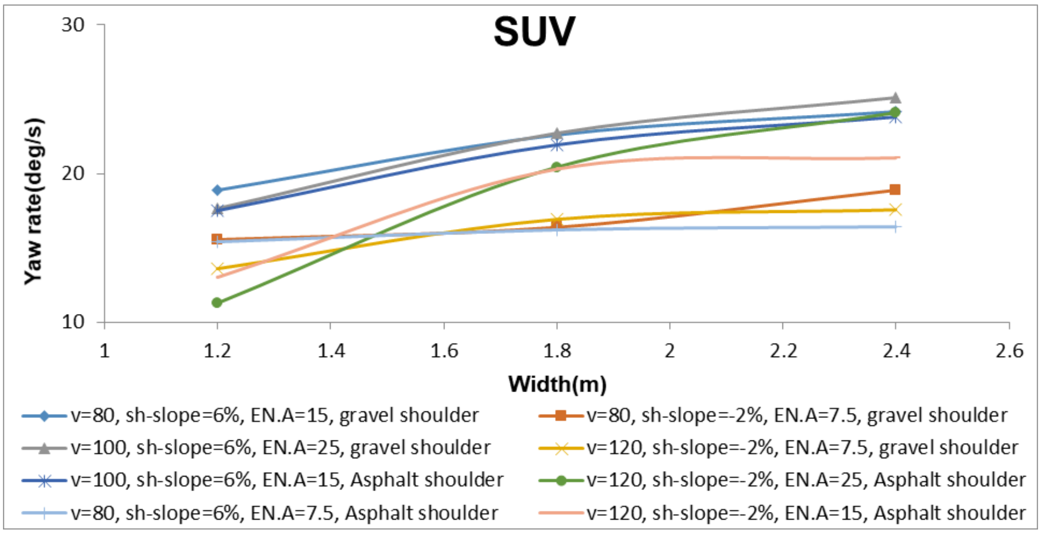
(a) The relation between shoulder width and the Sedan yaw rate

Fig. 5. The relation between shoulder width and vehicle yaw rate.(Continude)

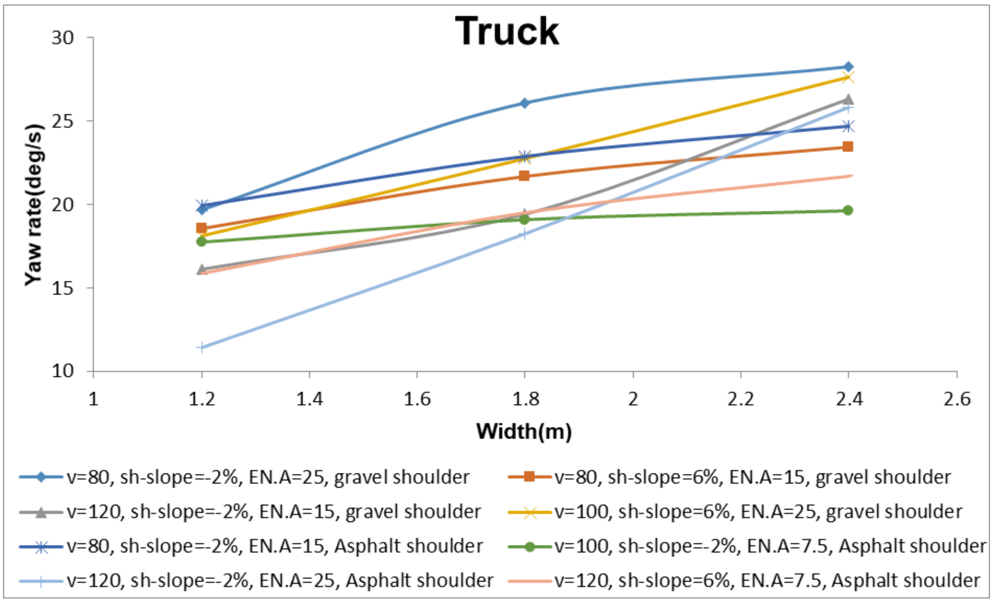
5(a)-(c) present simulation results for the relation between the amounts of yaw rate and shoulder width. In addition, the amount of road departure is equal to the amount of shoulder-width in all scenarios.

Yaw moment has a critical impact on skidding, which can lead to a rollover. Vehicle dynamic parameters and shoulder parameters have different effects on various types of vehicles as well as vehicle yaw rate. Analyzing the effects of changes in shoulder width on safety and considering vehicle yaw rate in different types of vehicles can lead to a more efficient shoulder design in horizontal curves, which can reduce skidding potential. Considering vehicle types and simulated scenarios, Figs. 5(a)-(c) show the effect of shoulder-width on the average amounts of yaw rate. The friction between gravel shoulder and tires is high, and due to that, the skidding and rollover risk decrease against the asphalt shoulder.

Fig. 5 illustrates scenarios where outer tires placed on both gravel and asphalt shoulder. Yaw rate values show that expanding the gravel shoulder from 1.2 to 2.4 m (which leads to higher risks of road departure), increases yaw rate values in all vehicle types (4, 5.45, and 7.08 deg/s for a Sedan, SUV, and Truck, respectively). In addition, when the outer tires sit on asphalt shoulder, yaw rate values can be increased by expanding shoulder width from 1.2 to 2.4 (3.7, 5.11, and 7.32 deg/s for a Sedan, SUV, and Truck, respectively). To analyze Figs. 5(a)-(c), the effective role of the vehicle suspension system and the geometric characteristics of the vehicle (width and CG height) should be taken into account in such a way that



(b) The relation between shoulder width and SUV yaw rate



(c) The relation between shoulder width and truck yaw rate

Fig. 5. The relation between shoulder width and vehicle yaw rate.

Table 3. Average yaw rate values (degree/s) based on CarSim and Trucksim simulation results.

Variable	Scenarios	Gravel shoulder			Asphalt shoulder		
		Sedan	**SUV**	**Truck**	**Sedan**	**SUV**	**Truck**
Sh-slop	**-0.02**	17.12	19.09	20.77	17.33	19.20	20.90
	0.06	16.77	19.09	19.84	16.93	19.22	20.04
Width	**1.2(m)**	14.72	15.92	16.45	15.03	16.24	16.45
	1.8(m)	17.41	19.97	21.01	17.63	20.11	21.19
	2.4(m)	18.71	21.37	23.53	18.73	21.35	23.77
Speed	**80(km/h)**	18.82	20.53	20.62	18.95	20.52	20.53
	100(km/h)	17.25	19.78	21.55	17.36	19.85	21.76
	120(km/h)	14.77	16.95	19.02	15.08	17.32	19.11
EN.A	**7.5(deg)**	14.85	16.46	17.63	15.05	16.55	17.75
	15(deg)	17.57	20.20	21.36	17.82	20.29	21.59
	25(deg)	18.42	20.60	21.94	18.52	20.86	22.07

the sedan with an appropriate geometry (low CG height from the road surface and high vehicle width) has the lowest yaw rate changes in wider shoulders (more running off amounts). On the other hand, an SUV with an appropriate suspension system and a width lower than that of a sedan can resist skidding and higher amounts of yaw rate as shoulder width increases (higher frequency of road departure). Although the truck type displays the highest amount of variation in yaw rate as shoulder width changes, its powerful suspension system prevents the vehicle from skidding. Regarding the geometric properties of different vehicles types especially trucks, it should be noted that the distance between the rear axle and the center of gravity impacts yaw rate. Higher distances increase the rotational moment and the skidding potential of the vehicle. Double rear wheels in the truck type help provide extra yaw rate tolerance, which allows the vehicle to maintain high yaw rate values. It can be concluded that as the distance between the horizontal curve center and vehicle increases by the enhancement of the vehicle running off, so the forces applied to all three vehicle types are increased by the enhancement of the vehicle running off (actually by increscent of the shoulder width). This increase differs by the geometric specifications and suspension system of the vehicles. Table 3 shows an overview of simulation results, which indicate the effects of the dynamic parameters of motion (i.e., speed and roadway encroachment angle), shoulder geometry (i.e., width and cross slope) on yaw rate variations in different types of vehicles considering shoulder material.

Based on the output data presented in Table 3, it can be inferred that the dynamic parameters of the vehicle, especially the roadway encroachment angle, which directly corresponds to steering, directly correspond to yaw rate. None of the vehicles rolled over under various conditions and yaw rate values. Generally, it can be concluded that yaw rate values increase as the rate of road departure increases in horizontal curves as the outer tires are on the shoulder and the inner ones on the roadway. Even in the case of a wider shoulder, the rollover potential increases due to the high amounts of yaw rate in run-off-road vehicles.

4- Statistical modeling

This research investigates the effects of dynamic parameters and shoulder type on yaw rate in the sedan, SUV, and truck types of vehicles. For each type of vehicle, a linear regression model is proposed to explain the effects of various variables on yaw rate. The linear regression modeling process is performed by SPSS statistical software. Regression models are employed to explain the relationship between the dependent variable (vehicle yaw rate) and independent variables (speed, encroachment angle, shoulder width, and shoulder cross slope under various tire placement conditions on a gravel or asphalt shoulder). These models are calibrated considering the regression coefficients, which are derived from the curves of simulation data. This section aims to

Table 4. T and F test results according to Eq. (2).

Model	T	Sig	F	sig
Speed	-9.05	0.00	55.59	0.00
EN.A	7.74	0.00		
Width	8.91	0.00		
Constant	13.09	0.00		

demonstrate the relationship between variables as in Eq. (1).

$$Y = \beta_0 + \beta_{1x_{i1}} + \beta_{2x_{i2}} + \ldots + \beta_{kx_{ik}} + \varepsilon_i \qquad i = 1, \ldots, n \qquad (1)$$

Where y is the response variable, xij, j=1,…,p denotes the explained variables, βj, j=1,…,p shows the vector of regression coefficients, (ε) is the error term of the statistical models known as residual and n shows the sample size. Generally, statistical modeling is based on several preliminary assumptions. The reliability of modeling depends on the accuracy of such assumptions. These preliminary assumptions are necessary to allow the use of complex statistical inference methods.

Model (2) shows the proposed model for Sedan vehicle deviated in a horizontal curve where the outer tires are placed on the gravel shoulder and the inner ones on the roadway.

$$\begin{aligned} Yaw\ rate = & -0.101 Speed + \\ & 0.197 EN.A + 3.322 Width - 18.063 \\ & \left(R^2 = 0.819\right)\ (2) \end{aligned} \qquad (2)$$

According to Eq. (2), shoulder width and encroachment angle have a positive correlation with the yaw rate, which means as these two parameters increase, the yaw rate will increase and when they reduce, the yaw rate will reduce. But speed and shoulder slope have a negative correlation with the yaw rate which means yaw rate will decrease with increasing the speed and shoulder slope, and vice versa.

The most significant preliminary assumptions underlying linear regression analysis verified by this research are as follows:

4- 1- The Linear relationship between explained and response variables

The general relationship between response and explained variables can be determined by drawing their scatter plot. For variables with a nonlinear relationship, conversions are used to obtain a linear relationship. Meanwhile, the linearity of the response and the explained variables in model 2 is verified.

4- 2- Normality of Model Residuals

Checking the normality of residuals can be conducted visually with a histogram or a quantile-quantile (q-q) plot. The Kolmogorov-Smirnov test is also a means of testing the normality assumption at a specific level of significance. In this test, H0 is the assumption of having normal residuals. If H0 is confirmed, the given residuals comply with the normal distribution. Considering that the P-value for model (2) is equal to 0.200, the assumption of normality of the residuals is confirmed. Fig. 6 displays the residuals histogram and q-q plot, which are used for determining the normality of residuals.

4- 3- Homoscedasticity of the Variance of Residuals

Any funnel-like pattern in the scatter plot of standardized residuals compared to the predicted values of standardized regression indicates that the variance of residuals differs at different levels of the explained variables. The uniform scattering of the residuals between two parallel lines demonstrates the homoscedasticity of variance. Fig. 7 presents the scatter plot of standardized residuals compared to the predicted values of the standardized regression of model 2. No funnel pattern in this figure indicates the homoscedasticity of the variance of residuals [19].

4- 4- Non-autocorrelation in residuals for various observations

This assumption can be verified by considering the autocorrelation matrix of residuals. The autocorrelation test of the residuals is conducted measuring the values of the Durbin-Watson test. The test statistic is calculated using the following formula:

$$d = \frac{\sum_{t=1}^{n} \left(e_t - e_{t-1}\right)^2}{\sum_{t=1}^{n} e_t^2} \qquad (3)$$

The approximate value of this statistic is equal to ((1-r) *2), in which r is the coefficient sample autocorrelation. ((1-r) *2) is always between 0 and 4 because -1≤ r ≤1. Low amounts of DW (lower than 1) weaken the non-autocorrelation in residuals assumption while higher amounts (more than 1) strengthen it. In model 2, DW is equal to 1.163, which

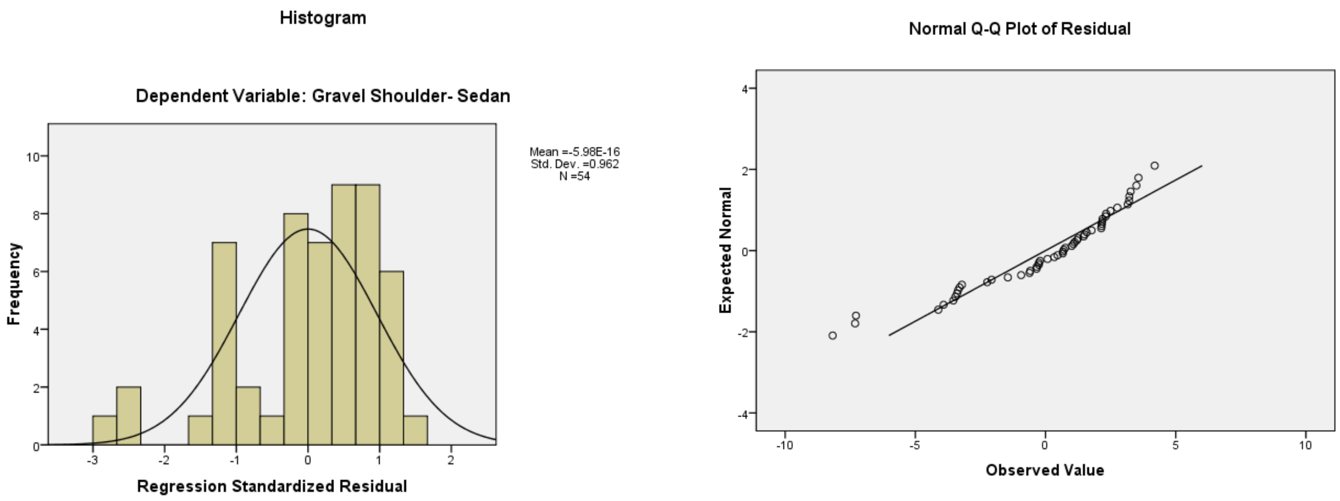


Fig. 6. Distribution of the residuals.

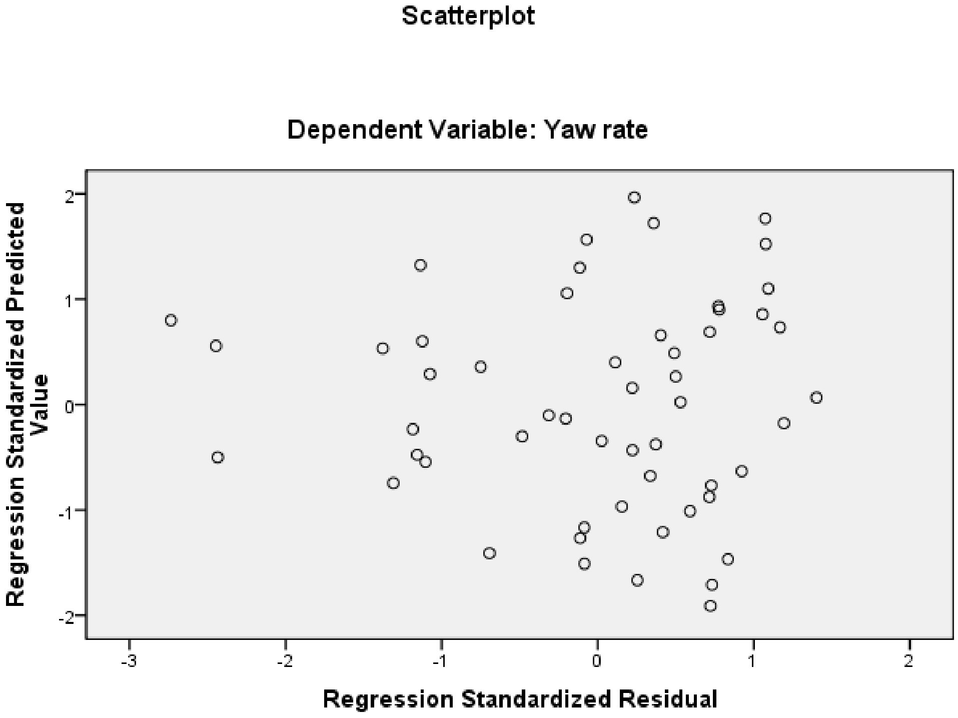


Fig. 7. Homoscedasticity verification of the residuals

Table 5. Statistics of Eq. (4); T and F test results.

Model	T	Sig	F	sig
Speed	-4.57	0.00	23.77	0.00
EN.A	5.06	0.00		
Width	6.96	0.00		
Constant	6.74	0.00		

Table 6. Statistics of Eq. (5); T and F test results.

Model	T	Sig	F	sig
Speed	-9.05	0.00		
EN.A	7.74	0.00	55.59	0.00
Width	8.91	0.00		

Table 7. Statistics of Eq. (6); T and F test results.

Model	T	Sig	F	sig
Speed	-8.63	0.00	50.85	0.00
EN.A	7.51	0.00		
Width	8.25	0.00		
Constant	13.25	0.00		

confirms the non-autocorrelation in the residuals assumption.

As mentioned before, the validation of a model is dependent on the validation of preliminary assumptions. If we fail to validate such assumptions, then the fitted model cannot be used for explanation or prediction purposes. The preliminary assumptions can be evaluated only after the model is fitted. In other words, the researcher conducting an analysis must fit the model based on observations. Assumptions should be validated after residuals are calculated.

In what follows, we propose additional linear models for different vehicles considering shoulder type and simulated scenarios. The validation of linear regression is performed for various conditions such as those in the model (2). In this study, all preliminary assumptions are validated for all proposed models.

Eqs. (4) and (5) present the proposed model of yaw rate for SUV and Truck vehicle types where outer tires are placed on a gravel shoulder and the inner ones on the roadway in horizontal curves.

$$
\begin{aligned}
Yaw\ \text{rate} = &-0.089 Speed + \\
&0.226 EN.A + 0.15 Sh.slope + \\
&4.542 Width + 16.284 \\
&\left(R^2 = 0.860\right)
\end{aligned}
\tag{4}
$$

For investigation of variable signs in Eq. (4) for SUV vehicle, it should be noted that shoulder width, shoulder slope, and Encroachment angle have a positive correlation with the yaw rate, that means as these parameters increases, the yaw rate will increase and as reduce, yaw rate will reduce, but speed has a negative correlation with yaw rate, i.e., yaw rate will decrease with increasing of speed, and vice versa.

$$
\begin{aligned}
Yaw\ rate = &-0.035 Ln\left(Speed\right) + \\
&0.233 EN.A - 12.154 Sh.slope + \\
&5.896 Width + 9.773 \left(R^2 = .897\right)
\end{aligned}
\tag{5}
$$

Also in Eq. (5) for the Truck vehicle, it is so clear that speed and shoulder slope have a negative correlation with yaw rate, i.e., yaw rate will decrease with increasing of speed and shoulder slope, and vice versa. However, shoulder width and Encroachment angle have a direct correlation with the yaw rate, which means as these parameters increase, the yaw rate will increase, and as reduce, yaw rate will reduce.

For situations where the outer tires sit on an asphalt shoulder in horizontal curves, the yaw rate models of Eqs. (6) to (8) are devoted for the Sedan, SUV, and Truck vehicle types, respectively.

$$
\begin{aligned}
Yaw\ rate = &-0.097 Speed + \\
&0.192 EN.A + 3.082 Width - 18.323 \\
&\left(R^2 = 0.843\right)
\end{aligned}
\tag{6}
$$

For rationality of variable's signs in Eq. (6) for the Sedan vehicle, it should be noted that shoulder width and encroachment angle have a positive correlation with the yaw rate, that means as these parameters increases, the yaw rate will increase and when they reduce, the yaw rate will reduce, but the speed and shoulder slope have an inverse correlation with the yaw rate, i.e., the yaw rate will decrease with increasing of speed and shoulder slope, and vice versa.

$$
\begin{aligned}
Yaw\ rate = &-0.080 Speed + 0.23 EN.A + \\
&0.578 Sh.Slope + 4.259 Width + 15.801 \\
&\left(R^2 = 0.857\right)
\end{aligned}
\tag{7}
$$

According to Eq. (7), for SUV vehicle, shoulder width, shoulder slope, and Encroachment angle have a positive correlation with the yaw rate, that means as these parameters increases, the yaw rate will increase and as reduce, yaw rate will reduce, but speed has an inverse correlation with yaw rate, i.e., yaw rate will decrease with increasing of speed, and vice versa.

$$
\begin{aligned}
Yaw\ \text{rate} = &\ 0.236 EN.A - 10.769 Sh.slope + \\
&6.102 Width + 9.505 \qquad \left(R^2 = 0.803\right)
\end{aligned}
\tag{8}
$$

Eq. (8) presents yaw rate model for the Truck vehicle, to control the valid ability of variable signs, it should be told that shoulder width and Encroachment angle have a positive

Table 8. Statistics of Eq. (7); T and F test results.

Model	T	Sig	F	sig
Speed	-4.23	0.00	23.515	0.00
EN.A	5.50	0.00		
Width	6.77	0.00		
Constant	6.78	0.00		

Table 9. Statistics of Eq. (8); T and F test results.

Model	T	Sig	F	sig
EN.A	4.15	0.00	18.59	0.00
Width	8.25	0.00		
Constant	13.25	0.00		

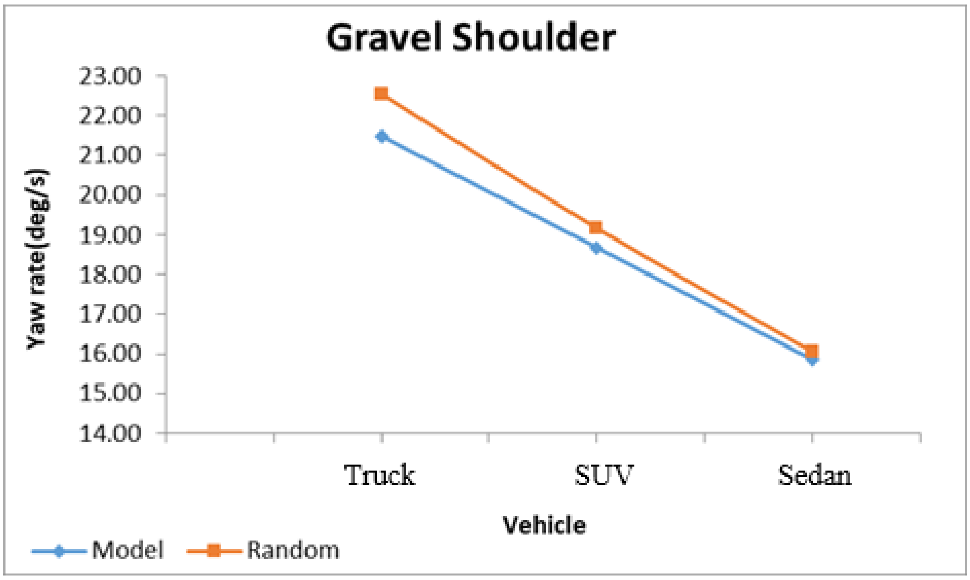


Fig. 8. The model calibration curve in gravel shoulders.

correlation with the yaw rate, that means as these parameters increases, the yaw rate will increase and as reduce, yaw rate will reduce. But speed and shoulder slope have an inverse correlation with yaw rate, i.e., yaw rate will decrease with increasing of speed and shoulder slope, and vice versa.

No model has been proposed for predicting vehicle yaw rates considering driver behavior. Thus, there is no real data for comparison, and the models proposed in this study are calibrated by the intact data from the simulation. For this aim, 20% of the output simulation data were randomly selected and excluded from the regression modeling process. After modeling, the intact data was applied to the model for calibration. The average calculated error of the models is 0.2 to 1.3 degrees per second. Regarding various parameters affecting the yaw rate and the limited number of parameters, thus error value is acceptable.

Figs. 8 and 9 show the average amounts of vehicle yaw rate based on the proposed model and the intact data related to each type of vehicle for gravel and asphalt shoulders, respectively. As the figures demonstrate, the amount of error is negligible.

5- Conclusion

This research investigates the dynamic simulation of 324 various scenarios of vehicle movement. The most significant results are listed below:

The effects of shoulder materials in highway design on different vehicle types are determined. Simulation results show that when the outer tires are on a gravel shoulder and the inner ones on the roadway in horizontal curves, the amount of yaw rate for Sedan, SUV, and Truck would be 1.06, 0.76, and 0.66 percent, respectively, which are lower than the cases in which the gravel shoulder is replaced with an asphalt one.

To enhance traffic safety, vehicle characteristics must be taken into account because they have an effective role in shoulder design. As the results of the simulated scenarios demonstrate, the average yaw rate of a Truck is 6.41 to 19.65 percent higher than the SUV and Sedan types, respectively.

Considering the yaw rate limitations of various vehicles, which are introduced by manufacturing companies and also result from a lack of appropriate safety criteria for yaw rate in AASHTO Green Book, the models generated by

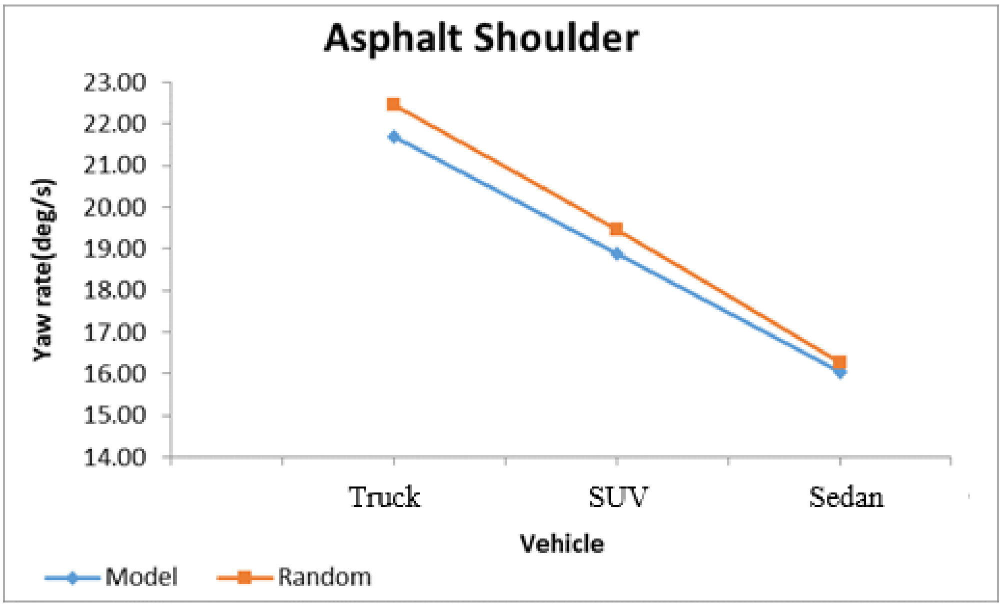


Fig. 9. The Model calibration curve in asphalt shoulders.

this study can be used in different design codes to provide more informed recommendations for shoulder design and speed limitations. With the use of presented models and the allowable yaw rate range of vehicles on the road, we could predict the speed limit. Also by utilization of predicted traffic parameters, we could design shoulder properties. In all speeds and all shoulder types, the maximum yaw rate refers to Truck and in all cases, the maximum yaw rate is at speed 100 km/h and asphalt shoulder. All amounts of yaw rate in all cases firstly have an upward trend up to 100 km/h then the take a downward trend up to 120 km/h. In cross-sectional slope, the maximum yaw rate was shown in slope 6%. The maximum variation refers to Sedan.

Although the amount of yaw rate and skidding potential directly correspond to the amount of road departure, a wider shoulder can prevent vehicles from moving to fore slopes, according to defined scenarios, as shoulder width increases, the vehicle could return to its previous situation easier and could recover itself faster and significantly reduce the rollover potential.

To enhance safety, we recommended that future studies consider longitudinal grades when evaluating the effects of shoulder parameters on yaw rate in horizontal curves via vehicle dynamic simulation. In such a situation, a more critical lateral acceleration is probably exerted on the vehicle and the geometry of the highway especially shoulder type (different materials, widths, and cross slopes), can prevent the vehicle from skidding and provide higher levels of safety. On the other hand, models presented in this study are restricted to vehicle type and road conditions. For expanding the models, the simulations can be done by more vehicle types under different weather conditions. In which, the factor of the dependent variables could be parametric and based on the vehicle type and weather conditions, the model can be derived and used in the road shoulder design. Another restriction of these models is that due to financial issues real data is not used to make a comprehension, which is pointed for the further studies.

References

[1] M.G. Karlaftis, A.P. Tarko, Heterogeneity considerations in accident modeling, Accident Analysis & Prevention, 30(4) (1998) 425-433.

[2] A. AASHTO, Policy on geometric design of highways and streets, American Association of State Highway and Transportation Officials, Washington, DC, 1(990) (2001) 158.

[3] T. Vaa, T. Assum, R. Elvik, Driver support systems: Estimating road safety effects at varying levels of implementation, TØI Report, (1202/2012) (2012).

[4] A.A. Kordani, B.T. Kallebasti, A. Attari, Effect of Shoulder Width and Drop-off on Vehicle Rollover and Shoulder Crossover Using Vehicle Dynamics Simulations.

[5] F. Gross, Jovanis, P. P., Eccles, K. A., & Chen, K. Y, Safety evaluation of lane and shoulder width combinations on rural, two-lane, undivided roads, 2009.

[6] H. Lv, N. Chen, P. Li, Multi-objective H∞ optimal control for four-wheel steering vehicle based on yaw rate

tracking, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 218(10) (2004) 1117-1123.

[7] D. Piyabongkarn, J. Grogg, Q. Yuan, J. Lew, R. Rajamani, Dynamic modeling of torque-biasing devices for vehicle yaw control, 0148-7191, SAE Technical Paper, 2006.

[8] H. Du, N. Zhang, F. Naghdy, Velocity-dependent robust control for improving vehicle lateral dynamics, Transportation research part C: emerging technologies, 19(3) (2011) 454-468.

[9] S. Chen, T.U. Saeed, M. Alinizzi, S. Lavrenz, S. Labi, Safety sensitivity to roadway characteristics: A comparison across highway classes, Accident Analysis & Prevention, 123 (2019) 39-50.

[10] M. Moomen, M. Rezapour, M.N. Raja, K. Ksaibati, Predicting injury severity and crash frequency: Insights into the impacts of geometric variables on downgrade crashes in Wyoming, Journal of traffic and transportation engineering (English edition), 7(3) (2020) 375-383.

[11] A. Brown, S. Brennan, on the required complexity of vehicle dynamic models for use in simulation-based highway design, Journal of safety research, 49 (2014) 105. 101-112.

[12] G. Qu, Y. He, X. Sun, J. Tian, Modeling of lateral stability of tractor-semitrailer on combined alignments of freeway, Discrete Dynamics in Nature and Society, 2018 (2018).

[13] N. FHWA-HRT-09-031, Roadside safety analysis program (RSAP)—engineer's manual, National Cooperative Highway Research Program (NCHRP) Report 492, National Research Council. Transportation Research Board, Roadside safety analysis program (RSAP)—engineer's manual, National Cooperative Highway Research Program (NCHRP) Report 492, 2003.

[14] AASHTO (Road side Design guide) American Association of State Highway and Transportation Officials, 4th ed., Washington, DC, 2011.

[15] D.J. Torbic, O'Laughlin, M. K., Harwood, D. W., Bauer, K. M., Bokenkroger, C. D., Lucas, L. M., and Varunjikar, T, NCHRP report 774 Superelevation criteria for sharp horizontal curves on steep grades., Transportation Research Board of the National Academies, Washington, DC, 2014.

[16] R. Ghandour, A. Victorino, M. Doumiati, A. Charara, Tire/road friction coefficient estimation applied to road safety, in: 18th Mediterranean Conference on Control and Automation, MED'10, IEEE, 2010, pp. 1485-1490.

[17] S. Melzi, E. Sabbioni, on the vehicle sideslip angle estimation through neural networks: Numerical and experimental results, Mechanical Systems and Signal Processing, 25(6) (2011) 2005-2019.

[18] R. Rajmani, Vehicle dynamic and control, in, Springer, 2006.

[19] A.A. Kordani, S. Javadi, A. Fallah, The effect of shoulder on safety of highways in horizontal curves: with focus on roll angle, KSCE Journal of Civil Engineering, 22(8) (2018) 3153-3161.

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