As a type of horizontal curve, the reverse horizontal curves (RHCs) are one of the most critical types of road locations where many accidents occur due to slippage resulting from the centrifugal force of the vehicles. These crashes can increase dramatically if the RHC is combined with a longitudinal slope (downgrade or upgrade). In this study, by using the vehicle dynamic modeling (VDM) method, the lateral acceleration of vehicles (including E-Class Sedan, E-Class SUV, and Truck) passing through the RHC combined with three scenarios of downgrades, upgrades, and no slope was evaluated. Finally, in order to present the final model, the RHC lateral acceleration model was presented based on the effective parameters, including different design velocities ($V$), the direct distance between two horizontal curves ($D$), and different longitudinal slopes ($G$) by the multiple regression model method. The results of the VDM modeling showed that the slide potential of Sedans, SUVs, and Trucks when crossing the RHC combined with the downgrade was more significant than the upgrade and the no-slope paths. On the other hand, the modeling results showed that the proposed models for Sedans and SUVs with a very high level of importance ($R^2$ equals 0.920 and $R^2$ equals 0.967) could be used to assess the safety of vehicles crossing the RHC. According to the mentioned models, increasing the speed ($V$) and reducing the direct distance ($D$) in both models reduced the lateral acceleration (increased safety) of both Sedans and SUVs.

1. Introduction

Vehicle safety is one of the most important branches of transportation engineering that can improve the final performance of the road. Despite how important it is, it is often not taken into account when roads are built. This has caused a lot of economic and psychological damage in recent years [1]. The road factor, along with two human and vehicle factors, plays an important role in road safety; thus, road safety can be improved by properly modifying road geometry [2].

Mountain roads require horizontal and vertical alignments and, of course, a combination of both. Due to challenging terrain, designing such alignments with an economic base is difficult. Engineers, therefore, lower the standard design of horizontal curves by using steep gradients and short vertical curves. The proposed solution may reduce safety because there is no quantitative guideline for combined alignments to guide designers [3]. Reverse horizontal curves (RHCs) are one of the most important parts of road locations where many accidents occur due to slippage due to the centrifugal force of the vehicles. RHC safety depends on several factors, the most important of which are the geometric characteristics of the road [4]. Due to the possibility of combining RHC with steep slopes (vertical alignment), the safety of this type of curve has decreased on mountainous routes. Therefore, it is necessary to evaluate the safety of the RHC combined with the vertical alignment. However, the geometric guide used for such curves is only given with a maximum value of 1.5 for the ratio between the largest radius and the smallest radius of the RHC and has not provided any other instructions for correcting the geometry of the RHC (combined with the path with and without slope) [5].

One of the main design parameters of horizontal curves is lateral acceleration. The safety problem arises in sharp horizontal curves where excessive lateral acceleration
reduces vehicle control [6]. When lateral acceleration is too great, it can cause discomfort to drivers because they must brake on curves and increase the risk of running off the road or colliding with other vehicles. The vehicle is at risk of sliding or rollover rotation when the lateral acceleration reaches a critical level [7]. Lateral acceleration is determined by the horizontal curve radius and vehicle speed. Although the driver controls the car’s speed, velocity is significantly affected by vertical alignment. Hence, when determining the acceptable horizontal radius for the RHC combined with the vertical alignment, the vertical alignment must be taken into consideration [8].

AASHTO uses the point mass model (PMM) to calculate the horizontal curve radius equation. PMM on a curve with a superelevation height and fixed radius is one of the simple vehicle models for designing horizontal curves [9]. One of the limitations of this model is that it ignores the difference in power distribution on the wheels and axles of the vehicle [10]. Also, another limitation of PMM is that it does not express inverse and compound curve calculations alone or in combination with a vertical path. These limitations led researchers to try to use other appropriate methods. Previous studies have examined the relationship between combined curve design and safety using computer-animated roadway displays [11]. However, some weaknesses, such as the dynamic task of driving and not collecting vehicle operation data, have limited their usage. Combining curve designs (vertical and horizontal alignment combinations) have also been studied through field studies [12, 13]. However, field studies are limited to current alignments. Therefore, the systematic manipulation of the geometric properties of the roads is not possible. In addition, it is difficult in field methods to capture continuously dependent variable data such as lateral acceleration, speed, and braking force [14].

Other methods, such as driving simulations, suffer from weaknesses such as simulator sickness and accurate replication of physical sensations. In order to solve these problems, a validation test before use is suggested for the study [14]. The Carsim and Trucksim software were used by one of the mechanical simulation corporations (MSC) to simulate the vehicle’s dynamics. Well-known companies in the automotive industry (including Ford) have used the above software for testing their vehicles. As a result, this software is not invalid; thus, this method could be a good option for studies in this field [1, 9]. One of the drawbacks of studies on the design of horizontal curves is that they do not consider the vehicle parameters in the equation of the geometric design. Therefore, the advantage of using vehicle dynamics modeling (VDM) is the effective characteristics of vehicles on the geometric design of the routes, which is considered one of the main objectives of this study, along with the lateral acceleration parameter. In this study, the VDM method was used as a dependent variable to study the safety of different vehicles passing through the RHC in three scenarios, including a downgrade, an upgrade, and a path without slope, in contrast to AASHTO’s assumption and most studies on the subject that used PMM. Finally, a multiple regression model was presented based on the parameters affecting the design (simulation results).

1.1. Literature Review. A review of previous studies shows that most of their focus has been on safety and vehicle operation in single curves (or noncombined). However, research shows that the probability of an accident in combined curves (e.g., the combination of a horizontal curve with a vertical alignment) is higher than that of separate horizontal and vertical curves [11, 15, 16]. Therefore, in order to develop new roadways, a good design requires the simultaneous development and study of horizontal and vertical curves to consider their effects on safety [14].

Lamm et al. concluded that road alignment affects road safety [17]. Regardless of the effect of vertical alignment on road safety, various studies have shown that curve radius also affects safety. Wilson [18] concluded that the accident rate in curves with a radius of fewer than 200 meters is up to five times higher than in curves with more than 900 meters [18]. Hanno [16] studied the relationship between horizontal and vertical curves using the linear regression method. The variables affecting the results include traffic flow, horizontal curve length, horizontal radius, vertical gradient, the percentage of the horizontal and vertical curves that overlap, and the ratio between horizontal and vertical curve radius. The results showed that some variables, such as traffic volume, curve length, and algebraic difference, have a positive relationship with accidents, and others, such as horizontal curve radius, overlap percentage, and the vertical distance of the intersection point regarding the horizontal curve, have a negative relationship. According to the results, horizontal curves that overlap with crest curves are more prone to collisions than those that overlap with sag curves. Therefore, it is recommended to avoid combining minimum horizontal curves with crest curves [16]. Bella [15] found that drivers experience a more significant speed difference than noncombined curves when crossing sag curves. In addition, it was concluded that the velocity behavior in the combined curves was different from the noncombined curves. Finally, it was concluded that considering combined and noncombined curves separately could lead to a more accurate design of combined curvature and thus increase their safety [19].

Lateral acceleration has been used as an engineering parameter to investigate the possibility of vehicles slipping in various horizontal curves. Kordani et al. [20] investigated the effect of a horizontal curve combined with longitudinal slopes by simulating different design vehicles (light and heavy) at different speed conditions. The results showed that trucks were exposed to more lateral accelerations on the downgrades and fewer lateral accelerations on the upgrades [20]. Wang et al. [3] investigated the effects of four parameters, including upgrade, downgrade, crest, and sag curves, on a vehicle’s lateral acceleration. The results showed that the radius of the horizontal curve and the amount of slope affect the lateral acceleration; however, the length of the curve was positively correlated only with the lateral acceleration in the crest curve. These studies addressed the different effects of different curves and provided guidelines for improving the design of combined curves but did not consider velocity changes that could reflect unsafe designs [3].
As mentioned in the introduction, computer simulations have been used to evaluate the safety effects of combined alignments. Furtado [7] used the VDM method to compare the stability of a vehicle in a minimum flat horizontal curve in a standard manner. The results show that the minimum radius recommended by the current geometric design guides in North America should be increased by about 3 to 16 percent. By using the VDM method, Easa and Dabbour [21] concluded that the radius required for trucks to pass should increase when the vertical alignment is combined with the intended path [21]. Dabbour et al. [8] investigated the minimum radius required for RHC on the main lines of the freeway based on the VDM method. The results showed that in order to maintain an acceptable level of drivers’ comfort and prevent potential rollover, it is necessary to increase the minimum radius requirement for RHC [8]. In a study by Easa and Halim, adding intermediate tangents with lengths of 0, 100, 200, and 300 m between two horizontal curves revealed that increasing the minimum radius of the existing design guide (from 5 to 27) is required to compensate for the effects of inverse curvature and vertical alignment. These tangential lengths reduced the “increase the minimum required radius” for truck stability [22]. Despite their application, these studies failed to compare lateral acceleration at different combined alignments systematically; hence, more research is suggested in this regard. Accordingly, the present study focuses on RHC lateral acceleration in three scenarios: without slope, downgrade, and upgrade using the VDM method and providing better design guidelines.

2. Methodology

The AASHTO PMM method for designing roads presented its results without considering the force distribution effect on different wheels of the design’s vehicles, the lack of vertical road path specifications effect, the dimensions of the design’s vehicles [10], and the lateral and longitudinal angles of the road’s surface and vehicle axis [23]. Therefore, the dynamic car simulation method has been used by engineers and researchers to eliminate some of the weaknesses of the PMM method. In fact, in this study, the VDM method was used to investigate the safety of RHC combined with a path with and without slope using the concept of lateral acceleration. First, the input data for the simulation is chosen. Then simulation tests are performed using Trucksim and Carsim simulation software. Finally, using the influential variable in the research (as an independent variable) as well as the lateral acceleration of different vehicles of the design (as a dependent variable), a multiple regression model is proposed.

2.1. Modeling’s Input Data

2.1.1. Road and Pavement Condition Geometric Plan. In this study, RHC combined with longitudinal slopes including upgrades (2+, +4, and +6%), downgrades (−2, −4, and −6%), and nonslope paths (0% slope) were studied for modeling purposes. By considering the longitudinal constraints on the main paths, velocities of 80, 100, and 120 km/h were used for the simulation. Seven scenarios were considered in order to express the position of the RHC combined with longitudinal slopes (Table 1). The design of the route plan includes left and right curves with a standard deviation angle of 90 degrees (same radius) and a straight path between the two curves (to reduce sudden superelevation changes). This route is designed according to the AASHTO Green Book Regulations for speeds of 80, 100, and 120 km/h. In this study, the direct distance was considered in five cases with the following conditions:

(A) Having the slope length on superelevation ($L_s$) and without having the opposite slope removal length ($L_r$) and a variable distance ($a = 0$)

(B) Having the length of the slope on the height ($L_h$) and having the removal length of the opposite slope ($L_r$) and a variable distance of ($a = 0, 10, 30, 50$ m)

As a result, the total number of simulation tests required for this study is equal to the number of scenarios $= 3 \times 3 \times 7 \times 5 = 315$. Finally, based on the parameters affecting the output of the simulation’s results and the using statistical analysis of the multiple linear regression model for lateral acceleration, different vehicles were presented as the primary dependent variable of the study.

Also, considering the asphalt pavement as the surface, in dry conditions (no precipitation), the maximum coefficient of the pavement is equal to 0.9. Given that scenarios such as speed, braking, gear, and steering affect the driver’s behavior, these variables were used and evaluated in the simulation. Due to the constant speed of the vehicle in the simulation, the brake and gear scenarios were assumed to be constant, and the only changes were in speed and steering. In the simulations performed, the vehicle moves at a constant speed of 80, 100, and 120 km/h. Also, the steering scenario was designed so that the driver could steer in a way that is always 1 meter away from the road’s axis.

2.1.2. Vehicles. The vehicles considered in this study included one type of Truck and two types of passenger vehicles (E-class Sedan, E-Class SUV) that are used in AASHTO’s Green Book. The dimensional specifications of these cars are given in Table 2.

3. Simulations and Modeling Outputs

One of the important parameters regarding vehicles’ safety, especially their stability against overturning, is the lateral acceleration while crossing the horizontal curve. In general, there are two terms for lateral acceleration: centrifugal acceleration and lateral acceleration. Centrifugal acceleration is a virtual acceleration that occurs when moving in a circular path and is in the opposite direction to the lateral acceleration of the center. Also, the acceleration due to the sum of the height and friction of the wheel on the pavement is called lateral to central or centrifugal acceleration. This study obtains the centrifugal acceleration of the vehicles’ centers of gravity through software outputs.
As shown in Figure 1, the maximum lateral acceleration of vehicles reaches its maximum when entering the first and second curves of the RHC and at the moment of changing the steering angle by the driver. (Z_his indicate the maximum potential for sliding for the design’s vehicle. However, the maximum lateral acceleration is slightly reduced along both the first and second curves due to the car’s springs and shock absorbers. It steadily continues until it exits the horizontal curve. Due to the vehicle’s lateral acceleration on the forces applied to the vehicle, the same interpretation can be applied to lateral and vertical forces. On the other hand, the straight path between the first and second horizontal curves resulted in the lowest lateral acceleration (vertical force and lateral force), indicating that this area was able to properly reduce the lateral acceleration of the vehicle passing through the RHC and minimize the possibility of vehicle sliding.

### 4. Results and Discussion

#### 4.1. Analyzing the Effect of Speed Changes and Direct Distance Changes (D) at the Upgrade Path on Lateral Acceleration for the Design’s Vehicles.

By using modeling outputs, various results can be achieved, such as comparing the lateral acceleration of design vehicles in different conditions at different speeds. Figure 2 shows the changes in lateral acceleration by changing the direct distance at different speeds. According to the results, the lateral acceleration of the sedan was independent of the straight path between the two curves; therefore, the results were very close to each other. As the longitudinal slope increased, the lateral acceleration at speeds of 80 and 100 km/h increased slightly, reducing safety. In contrast, a slight reduction in lateral acceleration at 120 km/h was obtained. As shown in Figure 2, the lateral acceleration of the Sedan decreased by an average of 8% and 21% (increasing safety) by increasing the speed from 80 to 100 and 120 km/h, respectively (in different direct paths D). This result was in conjunction with more control from the driver over the vehicle at upgrades and higher speeds. In addition, considering the car’s dynamic properties by the software may have led to this result. At a direct distance of $D = 116$ m, a speed of 80 km/h, and a slope of 6%, the maximum value for the Sedan was $a_y = 0.23529$.

The lateral acceleration of the SUV was slightly greater than that of the Sedan. According to the results, the lateral acceleration of the SUV was also independent of the direct path between the two curves in such a way that the results were very close to each other. As the longitudinal slope increased, the lateral acceleration at speeds of 80, 100, and 120 km/h decreased slightly (increased safety). It seems that with the increase in weight of the SUV compared to the Sedan, as the longitudinal slope of the road increases, the lateral acceleration of the SUV decreases. As can be seen in Figure 2, the lateral acceleration of the SUV decreased as the speed increased from 80 to 100 and 120 km/h, respectively.

<table>
<thead>
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<th>$V$ (km/h)</th>
<th>$R$ (m)</th>
<th>$e$ (%)</th>
<th>$M$ (m)</th>
<th>$L_c$ (m)</th>
<th>$L_t$ (m)</th>
<th>$L_r$ (m)</th>
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<td>230</td>
<td>8</td>
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<tr>
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<tr>
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<td>1875</td>
<td>2438</td>
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<tr>
<td>Height (mm)</td>
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<td>3200</td>
<td>1000</td>
</tr>
<tr>
<td>Weight (kg)</td>
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<td>1590</td>
<td>4457</td>
<td>6789</td>
</tr>
<tr>
<td>Distance between the wheels (mm)</td>
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<td>2950</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Height of the center of the wheel from the road surface (mm)</td>
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<td>390</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Height of the center of mass (mm)</td>
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<td>720</td>
<td>1173</td>
<td>1800</td>
</tr>
</tbody>
</table>

As shown in Figure 1, the maximum lateral acceleration of vehicles reaches its maximum when entering the first and second curves of the RHC and at the moment of changing the steering angle by the driver. This indicates the maximum potential for sliding for the design’s vehicle. However, the maximum lateral acceleration is slightly reduced along both the first and second curves due to the car’s springs and shock absorbers. It steadily continues until it exits the horizontal curve. Due to the vehicle’s lateral acceleration on the forces applied to the vehicle, the same interpretation can be applied to lateral and vertical forces. On the other hand, the straight path between the first and second horizontal curves resulted in the lowest lateral acceleration (vertical force and lateral force), indicating that this area was able to properly reduce the lateral acceleration of the vehicle passing through the RHC and minimize the possibility of vehicle sliding.

### Table 1: Characteristics of reverse horizontal curves simulated in the road plan.

### Table 2: Specifications of the vehicle used in the research.
Furthermore, on average, $D$ (for the reasons mentioned) decreased by about 8% to 21% (increased safety) on different direct paths. According to Figure 2, at a direct distance of $D = 116$ m, a speed of 80 km/h, and a slope of 2%, the maximum value for the SUV was $a_y = 0.23748$. For trucks, the average lateral acceleration first increases and then decreases as the speed changes from 80 km/h to 100 km/h and 120 km/h. The obtained lateral acceleration decreases by decreasing the length of the $D$ as well as decreasing the slope of the path. In addition, the negative values of lateral acceleration indicate that the Truck slides inward in the most critical conditions. At a direct distance of $D = 120$ m, a speed of 100 km/h, and a slope of 4%, the maximum lateral acceleration for the TRUCK vehicle is $a_y = -0.01577$.

![Simulation output includes lateral acceleration, lateral force, and vertical force.](image)
Figure 2: Lateral acceleration changes when direct distance changes at upgrades and speeds of 80, 100, and 120 km/h.
4.2. Analyzing the Effect of Speed Changes and Direct Distance Changes (D) on the Lateral Acceleration of the Design’s Vehicles on a Route Without Slope. Lateral acceleration changes when the direct distance changes (D) for speeds of 80, 100, and 120 km/h, as demonstrated in Figure 3. According to Figure 3, the lateral acceleration of all three types of vehicles showed different behavior. For Sedans and SUVs, lateral acceleration decreased (increasing safety) by increasing the speed from 80 to 120 km/h (and at constant D values). The reason for this result was the driver’s control over the car in a straight line and at a higher speed. In addition, considering the vehicle’s dynamic properties by the software may have led to this result. At a direct distance of D = 116 m, at a speed of 80 km/h, the maximum amount of lateral acceleration for the Sedan is a_D = 0.23474 and for the SUV a_D = 0.23761.

For trucks, the average lateral acceleration increased and then decreased by changing the speed from 80 km/h to 100 km/h and 120 km/h, respectively. Negative lateral acceleration values indicate that the Truck slides into the curve at 120 km/h due to the dominance of the vertical weight applied to the truck’s center of gravity over the lateral force. At a direct distance of D = 97.5 m and a speed of 100 km/h, the trucks maximum amount of lateral acceleration was a_D = −0.020078.

4.3. Analyzing the Effect of Speed Changes and Direct Distance Changes (D) at the Downgrade Route on the Lateral Acceleration of the Design’s Vehicles. Figure 4 shows the changes in lateral acceleration by changing the direct distance (D) at downgrades for different speeds. For sedans and SUVs, the average lateral acceleration decreased (increased safety) by increasing the speed from 80 to 120 km/h. It seems that the reason for this result was the driver’s control over the car at downgrades at higher speeds. In addition, considering the vehicle’s dynamic properties by the software may have led to this result. For speeds of 100 and 120 km/h, the lateral acceleration increased as the slope increased from −2 to −6 percent, which indicated a decrease in the safety of the Sedan and SUV in the mentioned situation. As a result, at a direct distance of D = 116 m, a speed of 80 km/h, and a slope of 2%, the maximum lateral acceleration for the Sedan is a_D = 0.23439. Also, at a direct distance of D = 116 m, a speed of 80 km/h, and a slope of −2%, the maximum value for the SUV was a_D = 0.23724.

For trucks, the average lateral acceleration increases and decreases as the speed changes from 80 km/h to 100 km/h and 120 km/h. In addition, the negative values of lateral acceleration indicate that the Truck is sliding inward in the most critical condition. When the Truck was passing at 120 km/h from the RHC in all three scenarios of upgrades, no slope, and downgrade, the increase or decrease in D had no effect on the lateral acceleration results. In the total sum of the results, at a direct distance of D = 180 m, a speed of 100 km/h, and a slope of 4%, the maximum lateral acceleration for the TRUCK vehicle is a_D = −0.01612.

5. Lateral Acceleration Modeling

After modeling and summarizing the results mentioned in the previous sections, a set of multiple regression analyses was performed on the SPSS software’s data. These analyses aim to provide new equations or models to evaluate the impact of different parameters on the lateral acceleration of different vehicles of the design. These models show...
Figure 4: Lateral acceleration changes by changing the direct distance ($D$) at downgrade mode and speeds of 80, 100, and 120 (km/h).
changes in lateral acceleration (dependent variable) based on the vehicle’s speed, vehicle type, longitudinal slope, and the direct distance between two curves as an independent variable. The purpose of the work is shown in the following:

\[ y = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_k x_{ik} + \epsilon_i, \quad i = 1, \ldots, n, \]  

where “\( y \)” is the response variable, “\( x_{ik} \)” is the explanatory variable, “\( \beta_i \)” is the regression coefficient, “\( \epsilon_i \)” is the statistical model error, and “\( n \)” is the sample size.

5.1. The Lateral Acceleration Models for Sedan, SUV, Truck, and Total. The obtained regression models were calculated with the statistical features presented in Tables 3 and 4 to calculate the lateral acceleration of Sedan, SUV, and trucks while crossing the RHC according to equations (2)–(5).

where \( \bar{V} \): is the vehicle’s speed when entering the RHC (km/h); \( \bar{D} \) is the direct distance of the RHC (m); \( \bar{G} \) is the longitudinal slope of the RHC (%); and \( \bar{V}_t \) is the vehicle type defined in three modes: Sedan is 1, SUV is 2, and truck is 3.

\[ ay - \text{Sedan} = 0.329 - 0.001V + \left( 2.037 \times 10^{-5} \right)D \left( R^2 = 0.920 \right), \]  

(2)  

\[ ay - \text{SUV} = 0.336 - 0.001V + \left( 8.569 \times 10^{-6} \right)D \left( R^2 = 0.967 \right), \]  

(3)  

\[ ay - \text{Truck} = -0.144 - \left( 6.068 \times 10^{-5} \right)G \left( R^2 = 0.001 \right), \]  

(4)  

\[ ay - \text{Total} = 0.466 - 0.001V' + \left( 8.592 \times 10^{-5} \right)D' - 0.146V_t \left( R^2 = 0.269 \right), \]  

(5)

As can be seen from models 2 and 3, the speed and direct distance (\( D \)) parameters are present in both models. The impact of these two parameters on the results of the sedans

| Table 3: ANOVA test results for the lateral acceleration of the design’s vehicles. |
|----------------|----------------|----------------|----------------|----------------|----------------|
| Model          | Sum of squares | df        | Mean square | \( F \)       | Sig.         |
| Sedan          | Regression     | 0.036     | 3           | 0.012         | 584.482      | 0.000\(^b\)  |
|                | Residual       | 0.002     | 101         | 0.000         |              | 1000.028     | 0.000\(^b\)  |
|                | Total          | 0.038     | 104         | 0.000         |              | 28.512       | 0.000\(^b\)  |
| SUV            | Regression     | 0.042     | 3           | 0.014         | 1000.028     | 0.000\(^b\)  |
|                | Residual       | 0.001     | 101         | 0.000         |              | 1000.028     | 0.000\(^b\)  |
|                | Total          | 0.043     | 104         | 0.000         |              | 28.512       | 0.000\(^b\)  |
| Truck          | Regression     | 0.012     | 3           | 0.004         | 0.038        | 0.990\(^b\)  |
|                | Residual       | 10.704    | 101         | 0.106         |              |              | 0.990\(^b\)  |
|                | Total          | 10.716    | 104         | 0.106         |              |              | 0.990\(^b\)  |
| Total          | Regression     | 4.517     | 4           | 1.129         | 28.512       | 0.000\(^b\)  |
|                | Residual       | 12.27     | 310         | 0.040         |              |              | 0.000\(^b\)  |
|                | Total          | 16.793    | 314         | 0.040         |              |              | 0.000\(^b\)  |

\(^a\)Dependent variable: \( \alpha \). \(^b\)Predictors: (constant), \( D \), \( G \), and \( V \).
and SUVs has been the same. Based on the results, the proposed models with $R^2 = 0.920$ and $R^2 = 0.967$ showed a very good curve-fitting that can be used to study RHC’s safety. However, the results showed that the proposed models for trucks and all vehicles with values of $R^2 = 0.001$ and $R^2 = 0.269$; hence, the use of these models for design purposes will be questionable. However, it is possible to improve the model by changing the modeling conditions and increasing the number of scenarios.

5.2. Checking the Validation of the Model. By considering the significant value of each variable, it was concluded that the speed and longitudinal slope variables have an excellent effect on the model for sedans and SUVs. However, the direct-distance variables, with values of 0.602 and 0.509 (for Sedans and SUVs, respectively), have little effect on the model (Table 4). On the other hand, by considering the significant value of each variable, it was concluded that all variables, including speed, slope, and direct distance, have a weak impact on the model for the Truck (Table 4). Therefore, the proposed model for this type of vehicle is unreliable. Finally, for the overall model, including sedans, SUVs, and trucks, and given the significant obtained value, it was concluded that the variables of speed and vehicle type have a relatively good effect on the model. However, the direct distance and slope variables, with values of 0.940 and 0.829, had little effect on the model (Table 4).

5.3. Normality of the Residuals. One of the methods for determining the normality of residues is the visual method with a histogram or a q-q diagram. The Kolmogorov-Smirnov test can also be used to determine the assumption of normality at a certain level of significance. The model’s residual histogram and q-q diagram are shown in Figure 5, indicating the residual’s normality for sedans and SUVs.
Also, the result of the Kolmogorov–Smirnov test confirms the normality at a significant level of 0.05 for Sedans (0.00572 for sedans, 0.00374 for SUVs). Therefore, these two models can be used by designers as a suitable tool to assess the safety of Sedans and SUVs crossing the RHC curve. On the other hand, for trucks and all vehicles, this resulted in 0.3255 and 0.19900, respectively. Although the intended model for trucks and all the vehicles did not perform well, it can be somewhat improved by increasing the statistical population and sample size in future studies.

6. Conclusion

As a prerequisite, this study examined the safety of RHC using vehicle lateral acceleration, including sedans, SUVs, and trucks, using dynamic vehicle modeling. The results of this study are valuable for designers and engineers due to the exorbitant cost of field study in this field. Based on the results, the proposed models for Sedans and SUVs with a high level of importance can be used to assess RHC safety. In addition, if the RHC was combined with the vertical alignment, the safety of various Sedans and SUVs was reduced based on the lateral acceleration results. However, the lateral acceleration of the Truck passing through the RHC on the non-slope route was more significant than on the sloping route. Hence, the safety of the Truck on the slope was further reduced. The following is a summary of the most important results:

(1) Studies have shown that in the RHC combined with the upgrade and downgrade scenarios, the average lateral acceleration for the Sedan and SUV was in a more critical condition than the RHC without a slope. The highest lateral acceleration of the Sedan vehicle is at upgrades and downgrades, at speeds of 80 and 80 km/h, the straight distance of 116 and 126 meters, and a longitudinal slope of 6% and 2%, respectively. Also, the highest lateral acceleration for the SUV was at upgrades and downgrades at a speed of 80 km/h, the straight distance of 116, and the longitudinal slope of 2%, respectively. This was while the lateral acceleration of the nonslope was slightly lower for both Sedans and SUVs. Therefore, it can be stated that the passage of Sedans and SUVs over the combined RHC with a vertical alignment reduces safety.

(2) The truck's average lateral acceleration in crossing a nonslope RHC was lower than the RHC combined with the upgrade and downgrade scenarios. The maximum lateral acceleration of the TRUCK vehicle is at upgrades and downgrades at the speed of 100 km/h, a direct distance of 130 and 180, and a longitudinal slope is 4% and −4%. This suggests that crossing the nonslope RHC causes the Truck to experience more critical conditions that designers must consider.

(3) As the design speed increased from 80 km/h to 120 km/h, the lateral acceleration for Sedans, SUVs, and trucks decreased due to the driver's control over the RHC curve. Hence, the safety of the cars passing through RHC is higher in all three scenarios: upgrade, downgrade, and no-slope path.

(4) Increasing the direct distance (D) length at higher speeds positively reduces lateral acceleration (increasing safety) for the sedan and SUV that cross the RHC combined with the upgrade. While for the downgrade route, the length of the direct route (D) has increased lateral acceleration (decreasing safety).

(5) At all speeds (80, 100, and 120 km/h) and slopes, the TRUCK’s average lateral acceleration was less than that of the Sedan and SUV due to its heavier weight. As a result, less potential for sliding can be inferred in all situations.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References


