A Review on Studies Based on Vehicle Stability and Safety on Rural Horizontal Curves

Y K Remya[1*], Anitha Jacob[2], E A Subaida[3]

[1] Department of Civil Engineering, SCMS School of Engineering and Technology, Karukutty, APJ Abdul Kalam Technological University, India 683576

[2] Department of Civil Engineering, Government Polytechnic College, Chelakkara, Thrissur,680586, India

[3] Department of Civil Engineering, Government Engineering College, Thrissur, APJ Abdul Kalam Technological University, India 680009

*Corresponding author: remyayk@scmsgroup.org

doi: https://doi.org/10.21467/proceedings.112.62

ABSTRACT

All over the world India bangs the top most position in crash deaths. Nearly 1.2 lakh people die every year on Indian roads. Crashes involving rolloverand lateral skidding are now responsible for almost 1/3 of all highway vehicle occupant fatalities. So, rollovers and skidding are more serious than other types of crashes. One of the major reasons for such incidents is vehicle instability at curves due to its inconsistent geometric design. This necessitates a review on current design guidelines followed in India. Many researchers have pointed out drawbacks of current design approach and a few have identified various influential factors which are significant in curve design to reduce rollover and lateral skidding. When some researchers conducted field studies to measure vehicle stability at selected curves, some carried out computer simulations. There are efforts to incorporate vehicular characteristics in curve design which is much appreciable. This paper aims to project efforts made by researchers to reduce vehicle instability at horizontal curves. Moreover, gaps in these research works and scope for further research are highlighted.

Keywords: crash, rollover, skidding, vehicle stability

1 Introduction

As per Ministry of Road Transport and Highways, New Delhi (MORTH), about 15% of road crashes on highways occur at horizontal curves among which 8% is due to vehicle overturning or lateral skidding. A closer look at the crash statistics records of a few years reveals that road crashes involving vehicle overturning and lateral skidding are increasing drastically, especially heavy vehicle crashes. Several studies are conducted to identify the factors causing road crashes and prevent them. Crashes are multi causal and are affected by numerous factors like geometric design, traffic volume, traffic composition, variation in speed between vehicles of the same class and different classes, weather, motivation for travelling, driver's attentiveness and so on (Aljanahi et al., 1999).

James McKnightet. al., 2008 conducted 'Large Truck Crash Causation Study' for 967 crashes, with 1,127 large trucks, 959 non-truck motor vehicles, 251 fatalities, and 1,408 injuries. The identified causes are misjudged speed, insecure loading, inattentiveness, loss of steering control, vehicle characteristics like tire, brake and suspension. Numerous research works are carried out by researchers across the world to identify influence of geometry on crash rate. Yingxue Zhang et al, 2009 identified curve radius, width, superelevation, transition curve and sight distance have important effect on traffic accidents. According to Sunanda Dissanayake and

Proceedings DOI: 10.21467/proceedings.112; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-947843-3-3

Niranga Amarasingha, 2012, highway design features such as horizontal curvature, vertical grade, lane width, and shoulder width influence the occurrence of large truck crashes.

Vivek Bhuseet al., safety engineers at JP Research India Pvt. Ltd, Pune, India conducted a study on rollover crashes involving passenger cars in India using accident data from 2011 to 2016. They observed that fatality rate in passenger cars was higher than in trucks. 45% of the passenger car rollover crashes were tripped and remaining 55% were untripped rollovers. 50% of passenger cars involved in rollover were SUVs and MUVs where as 39% were sedan and hatchback models and vans constituted 11%.

Current design guidelines for horizontal curves (point mass model) rely on the simple engineering mechanics of centrifugal force acting outward the curve being resisted by superelevation provided at the curve and lateral frictional force acting at tire-pavement interface. The point mass model is given by:

$$e + f = \frac{v^2}{gR}$$

Where e=superelevation, f = lateral friction factor, V=velocity of the vehicle in m/s, g = acceleration due to gravity, R=radius of the horizontal curve

This model consider vehicle as a point mass with whole mass of the vehicle concentrated at its centre. It does not take into account vehicular characteristics. i.e. it treats a motor cycle, a passenger car, a heavy truck/bus and a huge truck with trailer in the same manner (Harwood et al. 1994). Even though the model assumes that vehicle traverses a uniform circle at constant speed, the nature of horizontal curves in India is too complex comprising of compound curves, multiple curves and combined curves. No provision is made for the reduction of design lateral friction due to other driving modes such as braking or an erratic emergency maneuver (Kontaratos et al. 1994). Another reason for lateral instability of vehicles at horizontal curves is modern heavy vehicle design with optimum power/mass ratio to carry heavier load, their-by resulting in higher center of gravity position and lower rollover threshold.

2 Geometric design consistency and Vehicle stability

More than half of the total fatalities on rural highways are crashes that occur on curves (Lamm et al. 1992). Thus, curves and the adjoining transition zones become the most unsafe regions on rural highways. One of the main causes for crashes at rural highways is the lack of geometric design consistency, defined as the extent to which highway elements are designed to avoid dangerous driving manoeuvres and confirm safety (Al-Masaeid et al. 1995). Also, a consistent highway design certifies that successive geometric elements act in a synchronised manner, thereby producing harmonized driving without surprising events.

Highway geometric design consistency can be measured using either of these criteria (1) operating speed(2) safety by achieving vehicle stability (3) extend of driver workload (4)alignment indices

The point mass model is widely used to design horizontal curves on Indian highways. As stated earlier, since this method assumes that whole mass of the vehicle is concentrated at its centre and ignore the distribution of frictional forces between front and rear tires, Macadam et. al. in 1985 modified the point mass model to introduce a front and rear tire at distances a and b from the mass centre at which frictional forces are considered separately. This vehicle model is called bicycle model. But this model simply distributes the frictional forces equally to front and rear tires of the vehicle model. Later an extension to bicycle model is developed by adding width to the vehicle model (Two axle model). That is, two additional frictional factors are added for the outer wheels in addition to two frictional factors for the inner wheels. This model has its mass centre at a height h from the ground. Due to the effect of body roll and load transfer to outside tires during vehicle cornering, the friction factors that result from the two-axle model are not same as that obtained from point-mass formula (Wong 1978, Macadam et al. 1985).

A more precise full vehicle model is vital to predict behaviour of a cornering vehicle like lateral ride comfort, rollover propensity and handling. The most simplified vehicle dynamic model is a two degree of freedom bicycle model, representing the lateral and yaw motions. This model can be used to understanding the basics of vehicle dynamics. But, it donot reflect the suspension and tire characteristics.14-degree of freedom vehicle dynamics modelconsists of a single sprung mass (vehicle body) connected to four unsprung masses (wheels). This model being more precise predicts vehicle motion better than the bicycle model. But this model does not consider relative wheel movement with respect to body. So, as the degree of freedom increases, the vehicle model becomes more precise and gives accurate results. But the model becomes too complex.

3 Measures of vehicle stability

The vehicle instability at horizontal curves may be caused by two reasons: Lateral skidding and rollover. Passenger cars are more prone to skid laterally and heavy vehicles are more likely to overturn ((McGee 1981, Chang et. al., 2001, Said Easa et al. 2003, Mehrara Molan et. al., 2014, Eric Donell et. al., 2015, Al Abdi et. al.,2019). The risk of lateral skidding of a vehicle at horizontal curve can be determined by comparing the available lateral friction and lateral friction demanded. If the demanded friction is more than available one, the vehicle will skid laterally. Similarly, margin of safety again rollover can be found by measuring the lateral acceleration experienced by cornering vehicle. If the lateral acceleration experienced by a vehicle turns out to be more than its rollover threshold, the vehicle will overturn.

4 Different approaches to evaluate vehicle stability

As stated earlier, lateral friction at pavement tire interface and lateral acceleration experienced by the cornering vehicle are the main indicators of vehicle stability. There are different methods to measure these indicators. One such approach is to conduct full scale field tests. But they are time consuming, laboursome and consume large amount of resources. With the introduction of computer simulation technologies, testing of dynamic behavior of vehicles in a virtual 3D environment has become ordinary. Computer based modeling approach provides economic and safe method to examine dynamic behaviour of vehicles for different geometric design variables.

Some simulation tools commonly used for understanding vehicle performance and behaviour are

- Automated Dynamic Analysis of Mechanical Systems (ADAMS), from mechanical dynamics Inc.
- Carsim from mechanical simulation Corporation (Michigan, America).
- Trucksimfrom mechanical simulation Corporation (Michigan, America).
- MATLAB-Simulink from Mathworks
- ANSYS software

ADAMS, multi body simulation software can simulate moving parts of automobiles and load distribution on mechanical systems very well. TruckSim Mechanical simulation calculates the performance characteristics of heavy truck or a combination vehicle where as CarSim offers dynamic modeling and analysis of four wheeled vehicles. MATLAB-SIMULINK environment can be used to develop road-vehicle-driver model in the form of building blocks using graphical user interface but not very helpful for modeling very complex mechanical 3D systems (Raffaele Di Martino, 2012). ANSYS, a finite element analysis tool offers numerous platforms like ANSYS Mechanical, CFD and multiphysics simulation and hence is highly beneficial to solve any mechanical structural or automotive systems. But the computational power and time requirement is dependent on the mesh size.

Obviously, the final selection of simulation tool is the discretion of research worker and depends on the ultimate goal of research, because one does not need to model the entire physics of vehicle but only a part of it. It seems that best solution is to couple/integrate different compatible software to arrive at best results.

4.1 Lateral Friction as vehicle stability measure

Barnett in 1936, Stonex and Noble in 1940, Moyer and Berry in 1940conducted full scale field tests using ball bank indicator device to determine lateral friction available at tire-pavement interface. Average lateral friction factor was determined to be 0.15. The point at which driver feels discomfort of lateral shift or overturning and undergo immediate reaction like slowing down, steering, or braking was used to find lateral friction values. But many researchers pointed out that the design value of friction factor needs to be updated as it was developed many years ago(Harwood et al. 1994, Carlson et al.1999).In 1994, Harwood and Mason noted that lateral friction demanded was very high for a horizontal curve with overlapping vertical alignment. They also pointed out that lateral skidding occured when vehicle crossed the design speed even marginally or when vehicle traversed the curve at less than design radius. Later, Morrall and Talarico, 1995 found that using these lateral friction values in curve design resulted in safety issues during wet weather.

Lamm et al. (1995) evaluated design consistency based on vehicle stability using the difference between lateral friction demanded and supplied (Δf) as follows:

- Good design: $\Delta f \geq +0.02$ (improvements not needed)
- Fair design: $+0.02 > \Delta f \geq -0.02$ (relation between superelevation and operating speed but be utlised to ensure that lateral friction supply will accommodate lateral friction demanded).
- Poor design: $\Delta f < -0.02$ (to be redesigned).

Amirarsalan MehraraMolan in 2014 conducted vehicle simulation studies on combined horizontal curve with longitudinal grade. Based on their results, curves with downgrades experienced greater side friction factors. Also, Braking had a pronouncing impact on side friction factors, especially for a sedan car.

Behrouz Tavassoliet. al. in 2018 utilised vehicle multi-body dynamic simulation modelling to evaluate performance of following vehicles: sedan, utility vehicle and truck traversing several scenarios when horizontal curves were associated with vertical sag curves. Regression modelling was done to determine the maximum lateral friction demand created in various conditions. The outcome of their research stated that the probability of skidding increased when a horizontal curve was combined with a vertical sag curve. Moreover, the maximum lateral friction between the pavement and vehicle tire was found to occur when the lower part of the sag curve and midpoint of horizontal curve coincide.

The results of Ali Abdi et al (2020) were in contrast to Behrouz tavassoliet.a l, 2018. They concluded that the grade and relative position of horizontal and vertical curve to each other did not affect the lateral friction factor for the sedan and SUV, and could thus be neglected. But margin of safety against skidding decreased for a 3 axle heavy truck when it cornered a curve with longitudinal grade. This study also emphasised that curves with clothoid transition had considerable impact on increasing the margin of safety, especially for curves with high radius.

Proceedings DOI: 10.21467/proceedings.112
ISBN: 978-81-947843-3-3

Series: AIJR Proceedings
ISSN: 2582-3922

4.2 Lateral displacement as vehicle stability measure

Alice Boruah et al., 2019 conducted intensive literature review to discover different existing methodologies and equipment to measure lateral placement of vehicles at horizontal curves. The paper also presents various modeling approaches. They found that studies incorporating different types of curves, vehicles and roadside configurations are essential to develop more accurate lateral position prediction models.

The literature review done by Alice Boruah et al (2019) provides recent updates of lateral position measurement methodologies and equipments. In early 1970s to 2000s, video cameras mounted at a fixed position near the horizontal curve were used to measure lateral position of vehicles at horizontal curves. This was aided by reference markings on the surface of pavement. Some researchers used recording vehicles mounted with video cameras at suitable headway distance from the test vehicle. Spacek (2005) used 12 regular delineator poles equipped with a ultrasonic sensor, LCD display, infrared transmitter and receiver, electronic part with microprocessor, memory card holder, charge and batteries. The measuring unit was capable of measuring the lateral distance between measuring pole and the vehicle. With the advent of latest technologies, some researchers (Bella (2013), Hassan & Sarhan (2012)) used driver simulator approaches with drivers of varying age group and driving experience. Even though driver simulator techniques has the advantage in testing various conditions and suggested road improvements, discrepancies arise because the driving participants know that they are driving a simulator and their concentration levels and safety concerns may not be as fully realized as in real world scenario.

A few researchers (Imran et al. (2006), Maljković&Cvitanić (2016), Cerni&Bassani (2017), Eboli et al. (2017), Kozempel et al. (2014)) used GPS and GIS technology to measure lateral placement of vehicles on horizontal curves. One of the limitations of GPS method is the lack of standard matching algorithms. A few studies used LIDAR technology for lateral positon data collection. Statistical analysis of data collected shows that time of the day, the travel direction, vehicle type, operating speed and lateral placement of vehicle at point of entry had paramount influence on trajectory profile of vehicle at horizontal curve. Also, when passenger cars and trucks were compared, differences in lateral placement were found to be higher in cars than trucks.(Fitzsimmons et al. (2013)).

4.3 Lateral acceleration as vehicle stability measure

Lino O. Garcíaet. al., 1851 conducted field study on a five-axle tractor–trailer unit with various load combinations under actual operating conditions through curves of various radii. The loading conditions considered were empty, partially load, and loaded with bottled spring water packed in boxes. Even when, the tractor trailer unit travelled at or below posted design speed, the actual lateral acceleration experienced by both tractor and trailer unit exceed the expected values on the basis of geometric design characteristics. Vehicle carrying partial load displayed the highest chance to overturn with lateral acceleration values close to 90% of the corresponding rollover threshold. Clearly, this raises questions about the adequacy of current design guidelines against rollover.

Bedard J T in association with Transportation Association of Canada during 1986 developed mathematical models which predict rollover threshold of heavy trucks. He identified the important vehicle parameters which greatly influences rollover threshold as centre of gravity height, axle characteristics, tire characteristics and suspension characteristics. But he also pointed out the difficulty in determining these vehicle parameters with greater accuracy.

The basic measure of rollover stability is the static rollover threshold, expressed as lateral acceleration in gravitational units (g). The rollover threshold of passenger cars were always greater than 1 g. But for light trucks, vans, and SUVs, rollover stability wasin the range of 0.8 g to 1.2g. But unfortunately the rollover threshold of a loaded heavy truck was much below 0.5 g (Harwood et al. 1994, C. B. Winkler and R. D. Ervin, 1999). With worst case loading, the static threshold value may decrease upto 0.25 g.

Tang Hesien Chang,2001 highlighted the importance of vehicular characteristics in geometric design of horizontal curves. He conducted an analytical study by considering vehicle as a sprung mass with suspension characteristics to arrive at a better equation which can be used for design of horizontal curves. Design equations were presented for both passenger cars and trucks.

$R_{min} = \frac{V^2}{121(0.5e+f)}$ For passenger cars

$$R_{min} = \frac{V^2}{122.5(0.75e+f)} \text{For trucks}$$

Bayburaet. al., 2001 considered lateral jerk as the comfort criterion in geometric design of highways and defined lateral jerk as change of lateral acceleration with respect to time created by the centrifugal force on the horizontal curve. They stated that lateral jerk must be below the predetermined limit values for the safety and comfortable driving. Minimum Horizontal Curve Radius based on the Limit Value of Lateral Jerk was also presented. Said M Easa and EssamDabbor in 2003 evaluated the effect of vertical alignment on minimum radius requirements using computer simulation: VDM Road, especially using design vehicle as truck. For 3-D alignments, the results indicated that current design guidelines for minimum radius have to be increased by as much as 20% to achieve roll stability. Minimum radius of horizontal curve was derived by Baykal et. al., 2009 taking into account the limit value of the lateral acceleration as follows:

For highways, $R_{min} = \frac{V^2}{12.96(\sqrt{1+e_{max}^2}a_y + e_{max}g}$

Where R_{min} is minimum radius of curve, e_{max} is maximum superelevation and V is design speed

Research carried out by Jin Xu et.Al.(2014) in China compared the influence of curve radius and driver speed on lateral acceleration experienced by different variants of passenger cars. The lateral acceleration experienced by passenger cars was at comfortable level(<3.5 m/s2) for both six lane and four lane highways. But on two lane roads, the lateral acceleration experienced was above comfortable level (>8m/s2). They also arrived at the conclusion that driver speed has a positive correlation with lateral acceleration experienced by the vehicle only on two lane roads. Curve radius had a negative correlation with lateral acceleration experienced. Based on the results of Amirarsalan MehraraMolan, 2014, Downgrades witnessed greater lateral acceleration values for a truck than on upgrades. Mehrara et al., 2014projected that the most crash-prone part of a combined curve was point of curvature, because of the changes in the steering angle. At point of curvature, the propensity to rollover and skidding was 8.5% greater than at any other part of the curve. Faisal Awadallahet. al. 2005 related superelevation rates with vehicle speed beyond the speed limit at which drivers start feeling lateral acceleration.

$$e = \frac{(\frac{V+Vs}{3.6})^2}{gR} - fs$$

Where, e=superelevation rate in decimal form, V=design speed (kmph), Vx=speed increment above design speed before drivers feel lateral acceleration (kmph) g=gravitational constant, R=curve radius (m), fs=design side friction factor

Dhahir& Hassan, 2016 conducted reliability analysis using vehicle dynamics software CarSim to estimate lateral friction demanded and lateral acceleration experienced depending on the geometric characteristics of horizontal curves. A quantitative evaluation of curve design in terms of probability of failure (POF), probability of noncompliance (PNC), and reliability index (β) was provided in the paper.

Vehicle dynamics simulation by Ali Abdi et. al., 2017 was to analyse the effect of shoulder properties on vehicle roll angle. They concluded that the width, cross slope and material of shoulder influence the roll angle of vehicle. Xiaotong Dong et. al. in 2018 developed a high fidelity validated model considering chassis flexibility, suspension, tire characteristics and steering input. A three dimensional stochastic road was modelled. The lateral acceleration, roll angle and the yaw rate increased with the increase in the velocity and the steering wheel angle. Ali Abdi et al (2019) conducted multiple simulations using CarSim and TruckSim dynamic simulation softwares on following vehicles: a sedan, SUV, and truck. Speed, deflection angle of curve, gradient, and location of horizontal and vertical curves relative to eachother were the simulation parameters considered.The authors examined the lateral friction demanded and lateral acceleration experienced by the test vehicles. Deflection angle of curve had a significant influence on lateral acceleration experienced by the truck. Recently, Yanna Yin et al. (2020) conducted a simulation study by modeling human, road, and vehicle assembly for a utility truck with rear wheel drive. They investigated the effect of road geometry, speed and superelevation on the stability of the vehicle. For this, lateral acceleration and load transfer ratio was used as measure of vehicle rollover, side way force coefficient as a measure of vehicle skidding and side slip angle as measure of vehicle lateral drift. Simulation using CarSim software resulted that as super elevation and side way force coefficient increases, road safety margin in terms of rollover, skidding and lateral drift improves. But, safety margin decreases much as speed of the vehicle increases. A closed loop driver simulation for a quasi static rigid vehicle model with 27 degree of freedom was used.

5 Concluding remarks and scope for future research

Obviously, the rollover propensity of heavy vehicles is an important issue that has caught the attention of government agencies and engineers. This paper presents a review of existing literature on the vehicle stability at horizontal curves. Various lateral stability indicators: Lateral friction demanded by the vehicle, Lateral acceleration experienced by the vehicle and lateral position of vehicle are subjected to a closer look. The different factors contributing to the instability of the vehicle on a curve are investigated. The various data collection methodologies used over the decades from ball bank indicators, video cameras to latest driver simulation approaches and their benefits have also been presented.

Following are the major findings from literature:

- Current design procedure for horizontal curves does not consider vehicle characteristics like size, loading, suspension and tire characteristics etc.
- Current design procedure does not give proper guidelines to design other than simple horizontal curves
- Point mass model's adequacy to access vehicle motion is doubtful
- Lateral friction demanded at tire-pavement interface exceeds expected expected values even at slight increase in operating speed from design speed
- Lateral acceleration experienced by a cornering vehicle varies with position of centre of gravity of the vehicle and therefore depend on vehicle size and loading condition.

A closer look of the literature indicates that a limited number of factors like operating speed, curve radius and superelevation have been analyzed. Extensive studies relating to the negotiation of different vehicle classes on different types of curves can lead to significant insights which help in the development of the prediction models.

How to Cite this Article:

Remya, Y. K., Jacob, A., & Subaida, E. A. (2021). A Review on Studies Based on Vehicle Stability and Safety on Rural Horizontal Curves. *AIJR Proceedings*, 515-523.

References

Al-Masaeid, H. R., Hamed, M., Ela, M. A., and Ghannam, A. G. (1994). ‘‘Consistency of horizontal alignment for different vehicle classes.’’ Transp. Res. Rec. 1500, Transportation Research Board, Washington, D.C., 178–183.

Ali Abdi et al. (2015), Dynamic Modelling of the Effects of Combined Horizontal and Vertical Curves on Side Friction Factor and Lateral Acceleration, IOP Conference Series: Materials Science and Engineering.

Ali Abdi Kordani et al. (2015),Analysing the influence of Coinciding Horizontal Curves and Vertical Sag Curves on Side Friction Factor and Lateral Acceleration Using Simulation Modeling, International Symposium of Highway geometric design, Transportation Research Record.

Ali Abdi et al. (2017), The Effect of Shoulder on Safety of Highways in Horizontal Curves: With Focus on Roll Angle, KSCE Journal of Civil engineering.

Ali Abdi et al. (2020), Evaluation of Safety in Horizontal Curves of Roads Using a Multi-Body Dynamic Simulation Process, International Journal of Environmental Research and Public Health.

Alice Boruah and Akhilesh Kumar Maurya (2019),Vehicle’s lateral placement on horizontal curves:Aliterature review, Transportation Research Procedia 48 (2020) 1325–1333.

American Association of State Highway and Transportation Officials. (2001).”A Policy on Geometric Design Of Highways And Streets”. AASHTO, Washington, D.C.

AmirarsalanMehraraMolan (2014), Multi-Body Simulation Modeling of Vehicle Skidding and Roll over for Horizontal Curves on Longitudinal Grades, Research gate.

Barnett, J. (1936). “Safe Side Friction Factors and Superelevation Design”. Highway Research Board, Vol. 16, 69-80.

Bashar Dhahir and Yasser Hassan (2016),Reliability-Based Design of Horizontal Curves on Two Lane Rural Highways,Article in Transportation Research Record Journal of the Transportation Research Board.

Bedard J T (1986), Vehicle Rollover threshold evaluation, Roads and Transportation Association of Canada, Ottawa, Ontario.

Behrouz TavassoliKallebasti et al (2018), Lateral friction demand on roads with coincident horizontal and vertical sag curves, Proceedings of the Institution of Civil Engineers - Transport.

C. B. Winkler and R. D. Ervin (1999), Rollover of Heavy Commercial Vehicles, The University of Michigan Transportation Research Institute.

Carlson, P.J. and Mason, J.M. (1999). “Relationship Between Ball bank Indicator Readings, Lateral Acceleration Rates and Vehicular Body-Roll Rates”. Transportation Research Record 1658, TRB, National Research Council, Washington, D.C., pp. 34-42.

Dabbour, E., Easa, S.M. and Abd-El-Halim, A.O. (2003). “Design Guidelines for Horizontal Reverse Curves Combined with Vertical Alignments”. Proceedings, CSCE 31st Annual Conference, Moncton, NB.

Easa, S.M. (1994). “Design Considerations for Highway Reverse Curves”. Transportation Research Record No. 1445, TRB, National Research Council, Washington, D.C., pp. 1-11.

Eric Donnelet. al. (2015), Use of Side Friction in Horizontal Curve Design: A Margin of Safety 2 Assessment, International Symposium of Highway geometric design, Transportation Research Record.

Faisal Awadallah (2005), Theoretical Analysis for Horizontal Curves Based on Actual Discomfort Speed, M.ASCE, 844 / Journal of Transportation Engineering.

Federal Highway Administration (2001). “Recent Geometric Design Research For Improved Safety And Operations”. FHWA, U.S. Department of Transportation, Washington, D.C

G. M. Gibreel et al. (1999) , State of the Art of Highway Geometric Design Consistency, Journal of Transportation Engineering, 125(4): 305-313

Garcia et al (2003), Heavy Truck Dynamic Rollover: Effect of Load Distribution, Cargo Type, and Road Design Characteristics, Transportation research Record, Journal of transportation research board.

Harwood, D. W., J. M. Mason, J.M., Glauz, W.D., Kulakowski, B.T., and Fitzpatrick. K. (1990). “Truck Characteristics For Use In Highway Design And Operation”. Reports FHWA-RD-89-226 and FHWA-RD-89-227, US Department of Transportation, Washington, D.C.

Harwood, D.W. and Mason, J.M. (1994). “Horizontal Curve Design For Passenger Cars And Trucks”. Transportation Research Record 1445, TRB, National Research Council, Washington, D.C., pp. 22-33.

J. F. Morrall and R. J. Talarico (1999),Side Friction. Demanded and Margins of Safety on Horizontal Curves, Transportation Research Record.

\Jin Xu et al (2015), An Experimental Study on Lateral Acceleration of Cars in Different Environments in Sichuan, Southwest China, Hindawi Publishing Corporation Discrete Dynamics in Nature and Society Volume 2015, Article ID 494130, 16 pages

Kontaratos, Marios, Psarianos, Basil, and Yotis, Apostolos (1994). "Minimum Horizontal Curve Radius as Function of Grade Incurred by Vehicle Motion in Driving Mode". Transportation Research Record 1445, TRB, National Research Council, Washington, D.C., pp. 86 - 93.

Lamm, R., Choueiri, E. M., and Hayward, J. C., and Paluri, A. (1988). ''Possible design procedures to promote design consistency in highway geometric design on two lane rural roads.'' Transp. Res. Rec. 1195, Transportation Research Board, Washington, D.C., 111–122.

Lamm, R., Choueiri, E., and Mailaender, T. (1991). ''Side friction demand versus side friction assumed for curve design on two-lane rural highways.'' Transp. Res. Rec. 1303, Transportation Research Board, Washington, D.C., 11–21.

MacAdam, C.C., Fancher, P.S. and Segel, L. (1985). "Side Friction For Superelevation On Horizontal Curves". Transportation Research Institute, University of Michigan, UMTRI – 72895, Michigan.

Mehdi H et al (2016), Evaluating the effects of road geometry, environment, and traffic volume on rollover crashes, Taylor and Francis online, Volume 31, Issue 2: Special Issue on the Impact of Vehicle Movement on Exploitation Parameters of Roads and Runways

MehraraMolan, A. A., and Abdi Kordani (2014), A. "Multi-Body simulation modelling of vehicle skidding and roll over for horizontal curves on longitudinal grades." TRB Annual Meeting.

Moyer, R.A. and Berry, D.S. (1940). "Marking Highway Curves With Safe Speed Indications. Proceedings", Highway Research Board, Vol. 20, 399-428.

Raffaele Di Martino. Modelling and simulation of the dynamic behaviour of the automobile. Automatic. Université de Haute Alsace - Mulhouse, 2005.

Said M Easa and Essam Dabbour (2003), Design radius requirements for simplehorizontal curves on three-dimensional alignments, Canadian Journal of Civil engineering, volume 30, number 6.

SangDo Na et al (2015),Dynamic vehicle model for handling performance using experimental data, Advances in Mechanical Engineering, Vol. 7(11) 1–12

Stonex, K.A. and Noble, C.M. (1940). "Curve Design and Tests on the Pennsylvania Turnpike". Highway Research Board, Vol. 20, pp. 429-451.

SunandaDissanayake and NirangaAmarasingha, (2012), Effects of geometric design features on limited access highways, Mid America Transportation Centre.

Tang Hesin Chang et al (2001), Effect of Vehicles suspension on Highway horizontal curve design, Journal of Transportation engineering.

Transportation Association of Canada (1999). "Geometric Design Guide For Canadian Roads". Transportation Association of Canada (TAC), Ottawa, ON, Canada.

Wong, J.Y. (1978). "Theory of Ground Vehicles". Wiley and Sons Inc. New York.

Xiaotong Dong (2018), Rollover threshold investigation of a heavy-duty vehicle during cornering based on multi-body dynamics, Advances in Mechanical Engineering, Vol. 10(7) 1–13

Yanna Yin et al (2020),The Influence of Road Geometry on Vehicle Rollover and Skidding, International journal of Environmental Research and Public health.

Yingxue Zhang et al (2009), Analysis of the Relation between Highway Horizontal Curve and Traffic Safety, International Conference on Measuring Technology and Mechatronics Automation.