Defining Driving Behaviour Using Friction-Circle concept: An Experimental Study

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Abstract

Consistency in the geometric design of highway is one of the major factors to achieve while designing. In highway design consistency, vehicle stability is a significant concern to ascertain the safe traffic operation. Vehicles moving on curved roads (horizontal/vertical), experiences the excessive centrifugal forces, which leads to the vehicles roll-over or head-on collision accidents due to the instability of the vehicles. Also, the stability of the vehicles gets impacted by the serpentine motion due to the higher number of passing/overtaking manoeuvre of vehicles on the non-lane based heterogeneous traffic stream. More rapid acceleration, higher operating speeds, and frequent braking operations increases the tire-road frictional demands, causing vehicle instability while driving. Such behaviour increases the driver's discomfort and risk resulting in an unsafe driving condition. Hence, studying the driving behaviourregarding such vehicle's instability is important to know the design consistency level and the safe/unsafebehaviour of the drivers. Literature review yieldsthat the dynamic parameters like speed, lateral and longitudinal acceleration/deceleration of the vehicle are the three primary criteria to determine the driving behaviour. Also, it is observed that braking coefficient (or coefficient of friction) of a road is one of the main criteria to ascertain the safety of any roadway section through the g-g diagram or the friction circle concept. The present paper studied the driving behaviour (regarding risk taking/aggressiveness) of different type of vehicles on various terrain roads (in plain and hilly terrain). The proposed methodology is predicated on the dynamic equilibrium of the vehicles. The g-g diagram and the friction circle concept is used to characterise the driving behaviour. The objective of this study is to assess the driver's risk-takingbehaviour due to critical driving situations occurred by the vehicle instability. By using the friction coefficient factors of dry pavement condition for rural roads on plain and hilly terrain, the limit curve of acceleration vector ($\bar{a}$), as a function of speed is obtained.
Keywords:Driving behaviour; Risky/unsafe driving; Safe driving; Friction Circle; g-g diagram; Plain/Hilly terrain.

1. Introduction

Highway geometric design consistency is one of the significant factors in achieving the smooth and safe vehicular operation. Further vehicle stability is an important concern to ascertain the safe traffic operation. The effects of side friction and super-elevation provided on horizontal and vertical curves have a major impact on vehicle stability and highway safety. Vehicles moving on the horizontal/vertical curves experience the excessive centrifugal forces, which leads to the vehicles roll-over or head-on collision accidents (Gibreel et al.,

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1999). Also, the stability of the vehicles gets impacted by the serpentine motion due to the higher number of passing/overtaking manoeuvre of vehicles in non-lane based mixed traffic stream. In the case of manoeuvres like higher deceleration/braking, sudden lane change, and the change in direction within the lane increases the frictional demand. Larger frictional forces are required to keep the vehicle stable on its path. Also, the increase in traffic volume and speeds results in a faster reduction in the frictional capabilities of the pavement surfaces. The current statistics exhibits that maximum of the traffic accidents occurs by the vehicle instability caused due to the loss of friction between tire and road. Hence, studying the driving behaviourregarding the vehicle stability is important to know the design consistency level and the safe/unsafe behaviour of drivers. In the present paper, all the three dynamic parameters (like speed, lateral and longitudinal acceleration/deceleration) are used altogether to analyse driver's safe or unsafe driving behaviour on both plain and hilly roads. The present study is predicated on the dynamic equilibrium of the vehicles. The objective of this study is to assess the drivers' risk-takingdrivingbehaviour based on critical driving situations occurred due to vehicle instability.

During vehicular motion, driving dynamics considers the vehicle's properties and road characteristics. The concept of braking coefficient was initially developed by Lamm, (1973) and Lamm et al. (1991). Thisconcept suggests a quantitative perspective evaluation of the design consistency based on the difference between side friction supply and demand.The coefficient of friction equations and their values used in different countries (like Austria, Australia, Britain, Canada, France, Germany, Greece, South Africa, Sweden, Switzerland and United States) are discussed by Harwood et al. (1998) based on each country's stopping sight distance (SSD) design policy.Various authors have reported some specific dynamic parameters like longitudinal and lateral acceleration which can be used to characterize driving style (safe/unsafe or aggressive) of the driver (Biral et al., 2005; Klauer et al., 2009; Johnson and Trivedi, 2011; Shaour and Bodenmiller, 2011; Paefgen et al., 2012; Vaiana et al., 2014).Driving safety or vehicle stability also depends on frictional force of the road which depends on the coefficient of friction of the road and weight of vehicle (Lamm et al., 1996; Lamm et al., 1999; Gibreel et al., 1999; Lamm et al., 2002; Psarianos et al., 1998). This indicates one of the reasons why vehicles with different configurations experience different safety conditions while travelling on curved road segments. The friction demand may exceed from the available friction reserve for any manoeuvre. The formulations of vehicle dynamics claim that, although the side friction demand values remain in the range of those assumed by the point-mass model (since the various vehicles and road parameters do not significantly influence its magnitude), the longitudinal frictional demand result from a relationship of the vehicle characteristics and road parameters. In the past, various studies related to safety assessment were conducted for turning movements on curved roads using side friction (Hisaoka et al., 1999; Glennon, 1971; Wallman and Astrom, 2001; Kritayakirana, 2012; Singh and Taheri, 2015; Eboli et al., 2016).Chakraborty et al. (2015)andGhandour et al. (2010) proposed a new approach for estimating maximum tire/road friction coefficient to detect the loss of friction which directly impacts the road safety. Also, Donnell et al. (2015) describe various friction concepts used in horizontal curve design. They also compare the lateral friction margins for different vehicle types and operating speeds to friction supply curves developed based on field measurements on multilane rural highways. In the past studies, the researchers have developed a correlation between the driver's aggressiveness and their cautious behaviour based on parameters like headway, lane change, speed, turning angle of the steeringwheel,etc. (Wang et al., 2014; Taubman et al., 2004).

Hisaoka et al. (1999) stated that g-g diagram couldbe implemented for distinguishing the driver behaviour. The g-g diagram depicts both the longitudinal and lateral accelerations normalised with gravity in y-axis and x-axis respectively. Biral et al. (2005)stated that g-g diagram is one of the practical ways to characterisevehicle's driverbehaviour according to the driver's motion perception and the risk level acceptance. A prototype mobile application is developed by Vaiana et al. (2014) to evaluate the aggressiveness of the drivers by plotting vehicle's acceleration (longitudinal/lateral) on the g-g diagram. Biral and Lot, (2009) used an interactive analytical model to explain features of normalised acceleration diagram (g-g diagram) of racing motorcycles. Brach and Brach, (2011), presented a realistic version of the tire-force circle/ellipse which incorporates slip angle, traction slip, and the actual non-linear tire force.

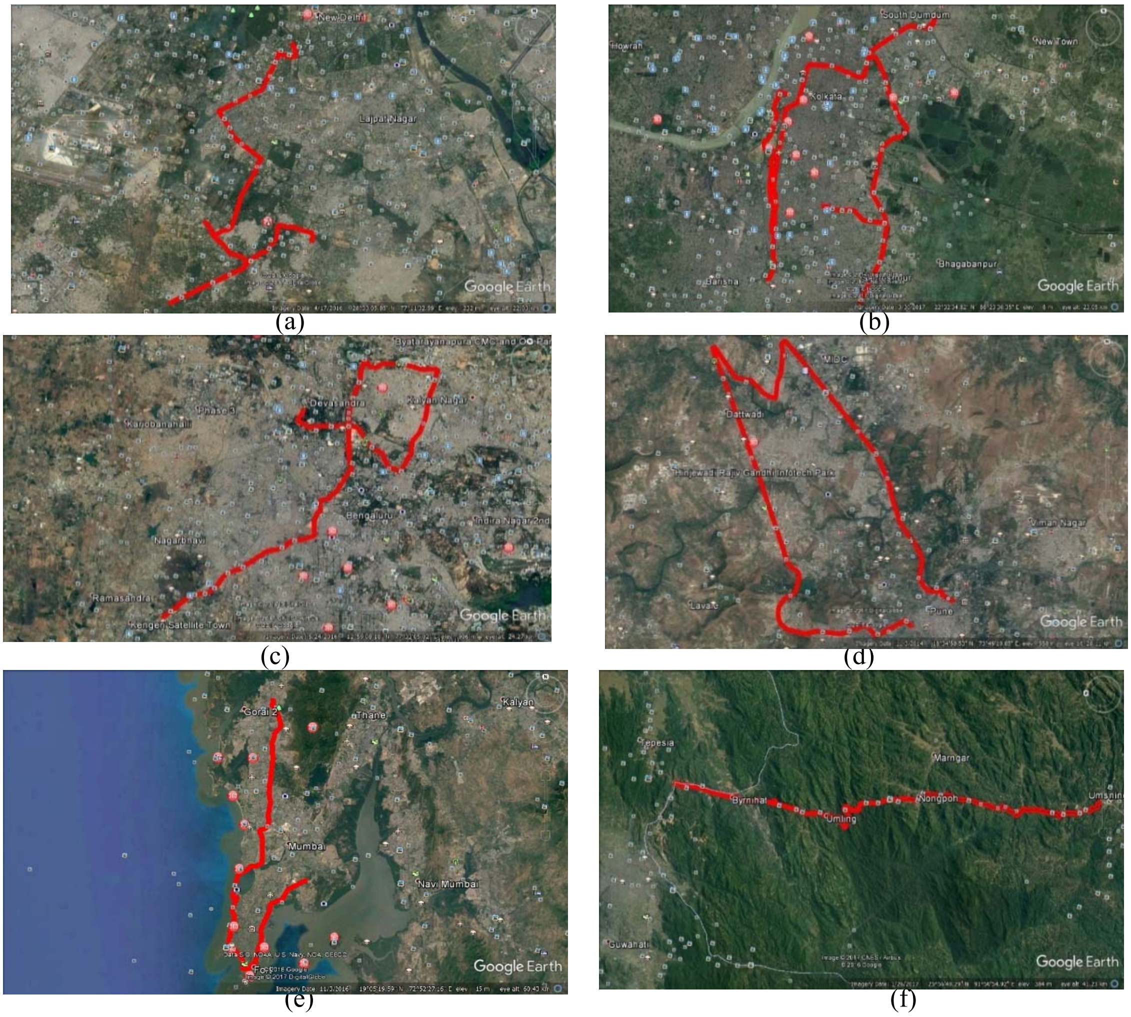
From the literature review, it is observed that the lateral acceleration, longitudinal acceleration, and operating speed are the three primary vehicular parameters to determine the driving behaviour of a vehicle. The safe driving on any roadway section mainly depends on braking coefficient or coefficient of friction. Also, g-g diagram or the friction circle/ellipse is one of the practical methods for characterising driving behaviourregarding the vehicle dynamics and risk perception level of the driver. Though many studies had been conducted to analyse the vehicle stability control or the safety assessment, most of the studies were carried out only on the curved sections with nearly homogeneous and lane disciplined traffic. In India, the heterogeneous and weak (or no) lane disciplined traffic leads to the serpentine motion (frequent lane change, change in direction within the lane,etc.) of vehicles also on straight roads resulting in higher frictional demand with discomfort to drivers. As many types of vehicles (with wide variation in their sizes and operating characteristics) are present in such traffic stream, the road safety is one of the major issues in such type of traffic stream(Psarianos et al., 1998). Hence the study of the driver behaviour in such mix traffic condition at the design friction coefficients as per Indian Roads Congress standard (IRC:66 1976) is highly recommended for both the plain as well as hilly terrain roads. Therefore, the present paper focuses on the study of the drivingbehaviour of vehicles on the plain and hilly roads of different cities based on the dynamic equilibrium of the vehicles. All the three parameters (operating speed, lateral/longitudinal acceleration, and braking coefficient) are used altogether to analyse driver's safe or unsafe driving behaviour over different roads. The g-g diagram or the friction circle method is used to characterise the driver behaviour of five different type of vehicles on both plain and hilly terrain.

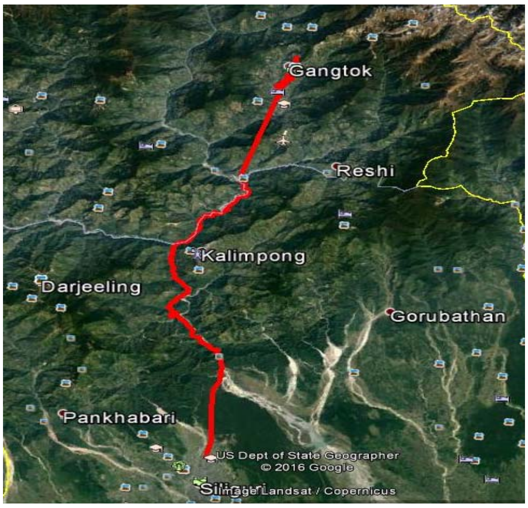
2. Study Methodology

The present study explores the operating speed and longitudinal/lateral acceleration of different vehicles (i.e. Sports Utility Vehicles,SUV; Sedan car; Hatchback car,H-Back;motorised three wheelers and motorised two wheelers) on roads of the various major cities of India. The road trajectory includes straight roads, curves, and roads with a different number of lanes on both plain and hill terrain. Video V-Box along with (GPS with 10 Hz data logging frequency) a display unit (for real time monitoring) are installed in the subject vehicles (hereafter referred as instrumented vehicle) which were used for data collection (Figure-1).

Figure 1. (a) Details of Video VBOX data recording Unit (b) Video VBOX installed in a car

Field data was collected by running different instrumented vehicles over different routes in the six major cities of India (refer Figure-2) in sunny weather during moderate to high flow conditions. The road surface was in good condition, and proper visible lane markings were present on all the selected routes.





(g)

Figure 2. Maps Showing the Road Trajectory of data collection in five major cities of India like (a) Delhi (b) Kolkata (c) Bengaluru (d) Pune and (e) Mumbai on Plain Terrain and (f) Guwahati-Shillong Hill Road (g) Siliguri-Gangtok hill road (the red lines in the maps indicates the marked road sections)

Five type of vehicles likemotorizedtwo-wheeler (2W), three wheelers (3W), SUV, sedan and H-back are three categories of passenger cars (Car And Bike Team, 2016) are used for data collection at plain road terrain. The plain terrain data are collected from five different cities of India namely Delhi, Kolkata, Bengaluru, Mumbai, and Pune with different trajectory lengths (40 km in Delhi, Kolkata, and Mumbai; 65 km and 70 km in Pune and Bengaluru respectively). The trajectories include different type of horizontal curves, turnings, intersections U-turn,etc., with a different number of lanes (four lanes and six-lane divided roads) to see the overall driver behaviourof different vehicles onplain terrain. However, only one type of car (SUV) is used for the hilly terrain data collection. A four-lane divided hill road trajectory of 60 km length (Guwahati-Shillong highway) and a two-lane bi-directional road of 80 km length (Siliguri-Gangtok road) are used for data collection. The instrumented vehicle (SUV car installed with Video-VBOX) traverse twice across the selected hill road trajectories to obtain sufficient data. The entire trajectory includes different horizontal and vertical curves with wide variation in radius and gradients. The lateral and longitudinal acceleration data along with longitudinal speed are extracted from the recorded VBOX data using VBOX-Tools software. Data from six different cities (both Plain and Hill terrain) for different vehicle types are extracted. The detailed procedure for data collection using the instrumented vehicle and its extraction are provided in Mahapatra and Maurya, (2013)&Mahapatra and Maurya, (2015).

The lateral and longitudinal acceleration, speed and tire-road friction (friction coefficient) are the major parameters, to determine the driving behaviour. In the present study, all three parameters are used all together to analyse drivers' safe/unsafe (risk taking/aggressive) driving behaviour on the roads of plain and hilly terrain using the g-g diagram or the friction circle concept. The tire-force ellipse and tire force circle are referred as frictioncircle and friction ellipse to illustrate the concept of tire-road interaction, i.e. the limiting force for both braking and steering (combined tire-force) (Brach and Brach, 2011).The equation of the tire-force circle/ellipse is used in the development of vehicle dynamic simulation software. The resulting diagram is simplified to a basic circular shape by considering the identical tire concept. Racer drivers use the concept of friction-circle to conceptualise their limit. The g-g diagram is used to translate this concept. These limits can be represented by a friction circle (lateral and longitudinal acceleration on x-axis and y-axis respectively). Hence, the driver behaviouris evaluated by using friction-circle concept presented by the g-g diagram (Figure-3). The maximum resultant friction coefficient is the radius of the friction circle. It is calculated with the maximum coefficient of longitudinal friction (μ_x) and the lateral friction (μ_y) provided for the design purpose.

$$\mu^2 = \mu_x^2 + \mu_y^2 1$$

whereμ_x= a_x/g and μ_y =a_y/g[a_x=longitudinal acceleration/deceleration &a_y is the lateral acceleration (right or left turn) of a vehicle]

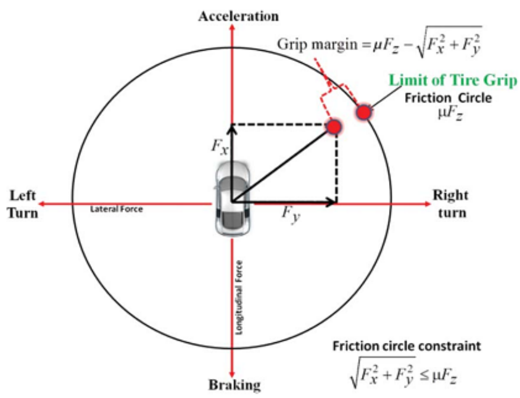


Figure 3. Friction Circle (Singh and Taheri, 2015)

Based on the Newton's second law of motion, the friction force and acceleration are associated with each other. The accelerations of a vehicle can be measured more easily than the frictional forces. A vehicle is subjected to an acceleration vector ($\bar{a}$), which have two components, longitudinal acceleration in the direction of mobility (a_x) and lateral acceleration in the transverse direction of mobility (a_y) of the vehicle.

$$|\bar{a}| = \sqrt{(a_x)^2 + (a_y)^2} 2$$

By considering longitudinal and lateral friction, and the concept of the ellipse of adherence, Eboli et al.(2016) obtained a circumference representing a limit between the safe and unsafe driving conditions. Assuming a constant value of friction factor and there is no super elevation, obtained the formulation for acceleration vector;

$$\bar{a}^2 = (a_x)^2 + (a_y)^2 = (g.\mu)^2 3$$

Where, g= gravitational acceleration &μ= maximum permissible coefficient of friction or braking coefficient

The above equation represents a circumference radius of ($g.\mu$), cantered at origin, where lateral and longitudinal accelerations are plotted on y-axis and x-axis respectively (Figure-4).

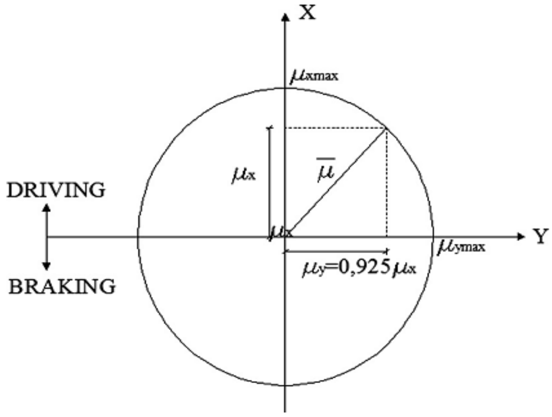


Figure 4. Limit between safe and unsafe driving conditions using an ellipse of adherence (Eboli et al., 2016)

Using the friction coefficient factors of dry pavements for rural roads, the limit curve of acceleration vector ($\bar{a}$), as a function of speed was obtained. The braking coefficients provided by different countries are different according to their design guidelines. The acceleration limit for safe driving are calculated by Eboli et al.(2016) for every operating speed according to their provided maximum permissible longitudinal/lateral coefficients of friction (Figure-5).

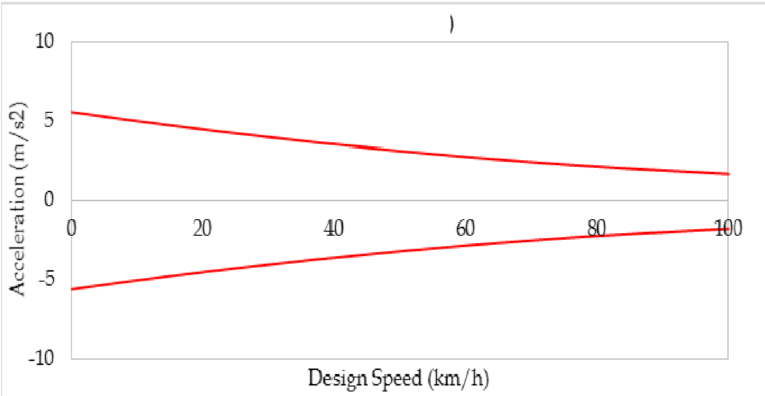


Figure 5. Safe Acceleration Limit Curve (Eboli et al., 2016)

This study considered the braking coefficients for plain and hilly terrain from the Indian Roads Congress design guidelines (IRC:66, 1976;IRC:86, 1983). The acceleration diagram in space (distance travelled) are obtained for identifying the most safe/unsafe behaviour of all vehicles throughout the trajectory. The diagram presents acceleration vector ($\bar{a}$), as a function of progressive (space), and the points where ($\bar{a}$) exceeds the limits (safe limit curve, a function of speed).

In the present paper, driving behaviour of a different type of vehicles are analysed for both plain roads and hilly roads separately. The following Section-3 describes the analysis of the driving behaviour of all five type of vehicles in plain terrain. The driving behaviour of SUV cars on hilly roads are presented in Section-4.

3. Driving Behaviour Analysis on Plain Terrain

The acceleration data (longitudinal, lateral) and speed are extracted vehicle type wise using the VBOX Tools software for all cities. Then the statistical significance between the data obtained from each city for different vehicles is tested using t-test at 5% significance level. The data with no significance difference between the various cities for the same vehicle type at 5% significance level are combined to see the generalisedbehaviour of drivers for each vehicle type throughout the country.

3.1. Acceleration Study

The longitudinal and lateral acceleration are plottedon the operating speed of the different vehicles in Figure-6(a) and 6(b) respectively. The scatter plots indicate that there is an inverse relation of speed with the lateral and longitudinal acceleration at the higher speed ranges (i.e. speed > 20-30 km/h). However, at the lower to medium speed both the acceleration follows a different trend with the increase in speed. The lateral acceleration islower at the near zero speed then it increases with the increase in speed up to medium speed (i.e. speed < 30 km/h) (Figure-6b). However, there is no such variation in longitudinal acceleration is observed at lower speed ranges (Figure-6a).

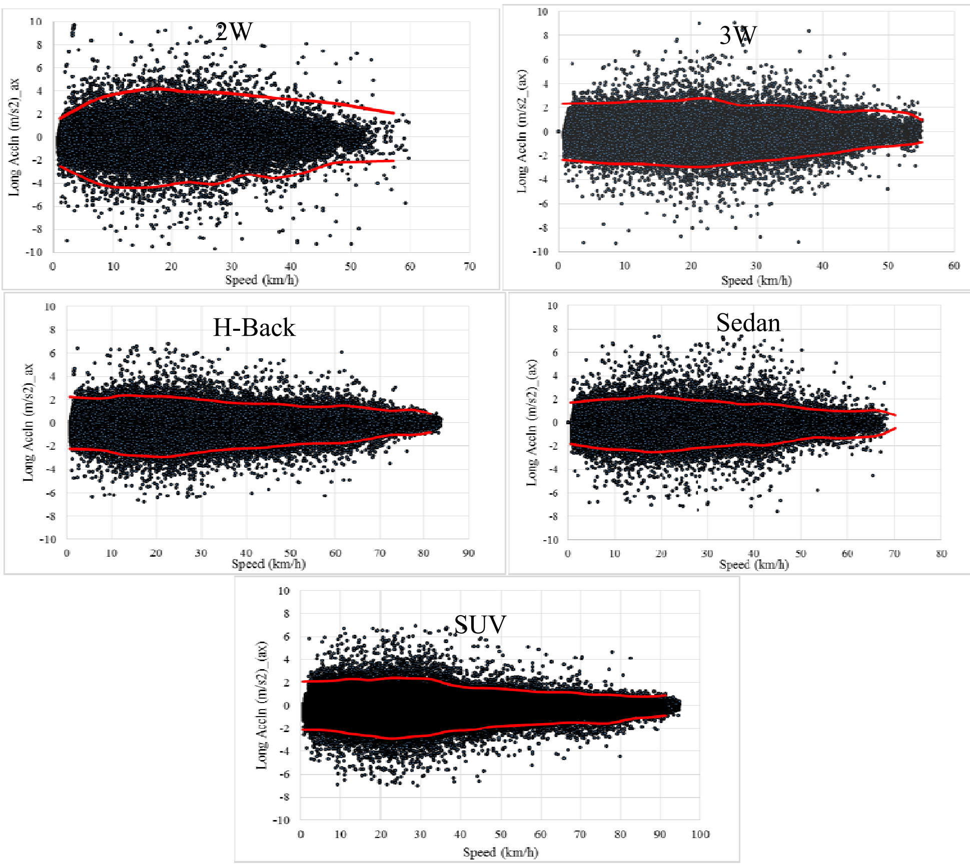


Figure 6(a). Scatter plot of longitudinal acceleration (a_y) on Operating Speed of Different vehicles (99percentile limit)

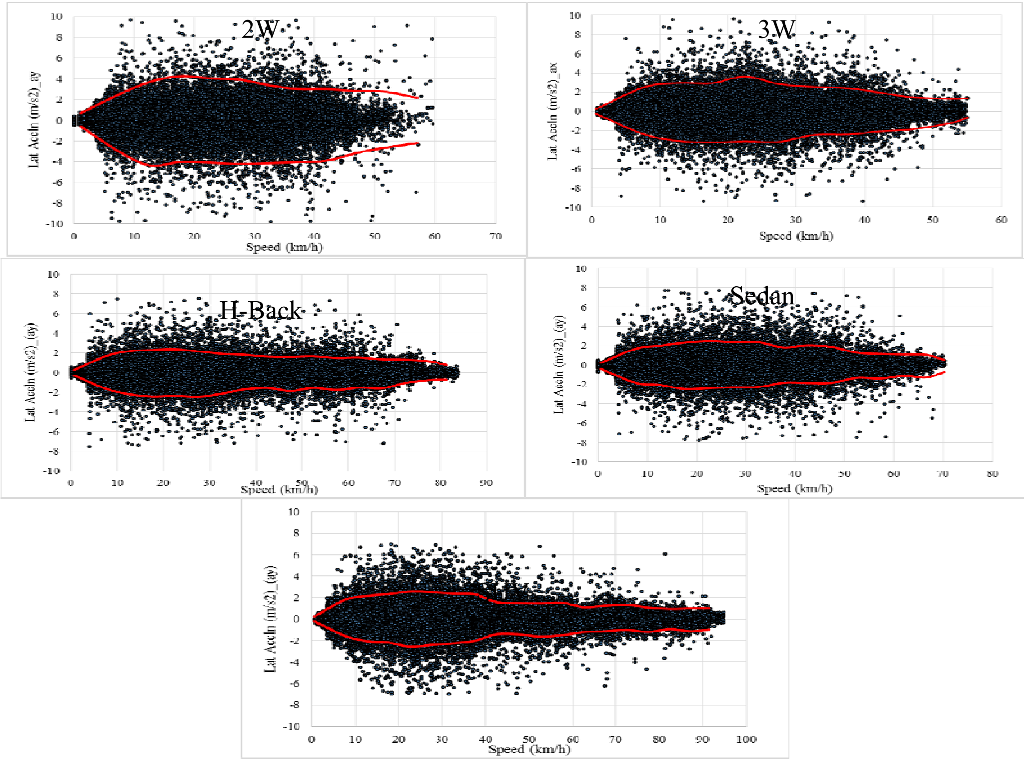


Figure 6(b). Scatter plot of Lateral acceleration (a_x) on Operating Speed of Different vehicles (99thpercentile limit)

The decreasing trend at higher speed indicates that the drivers perceive higher risk with speed over a certain limit yielding a reduction in the accelerations range (lateral and longitudinal). This limit is different for each driver. The limit shown in the above figures are the 99 percentile limit, (i.e. 99% data lies within the limit curve shown in the above figure). It can also be observed that in all vehicle cases, the lateral acceleration at very lower speed (i.e. the near zero speed < 5km/h), there are very fewer observations were found. This may be due to the minimum curvature radius experienced by the driver while driving (Bosetti et al., 2014). A similar result was observed by Bosetti et al. (2014) at the curvature roads less than 10m radius. In our present study, the detail data of the road curvature and turnings are not available.

As stated in the previous sections, both longitudinal and lateral accelerations are the two important parameters for evaluating driver behaviour. The above Figures-6(a) and 6(b), says the relationship among longitudinal and lateral acceleration individually with operating speed. To see the correlation between longitudinal and lateral acceleration and to analyse the driver behaviour g-g diagram is plotted.

3.2. g-g Diagram

As mentioned earlier, the g-g diagram is a very useful way of characterising the vehicledriverbehaviour. The g-g diagram for all five type of vehicles (2W, 3W, H-Back, sedan and SUV cars) are plotted by combining both the longitudinal and lateral acceleration (a_x anda_y). The diagrams show, the lateral accelerations and longitudinal accelerations normalized with respect to gravity in both horizontal and vertical axis respectively as the representation of friction circle in Figure-7. The Positive longitudinal acceleration indicates acceleration whereas negative indicates the deceleration of the vehicles. Similarly, the positive and negative lateral acceleration indicates right and left turn of the vehicles respectively. The longitudinal and the lateral accelerations are the combination of vehicle dynamics and diver's perception to the risk level he/she accepts to manoeuvre. So, the g-g plot is considered as the representation of actual driver behaviour performance.

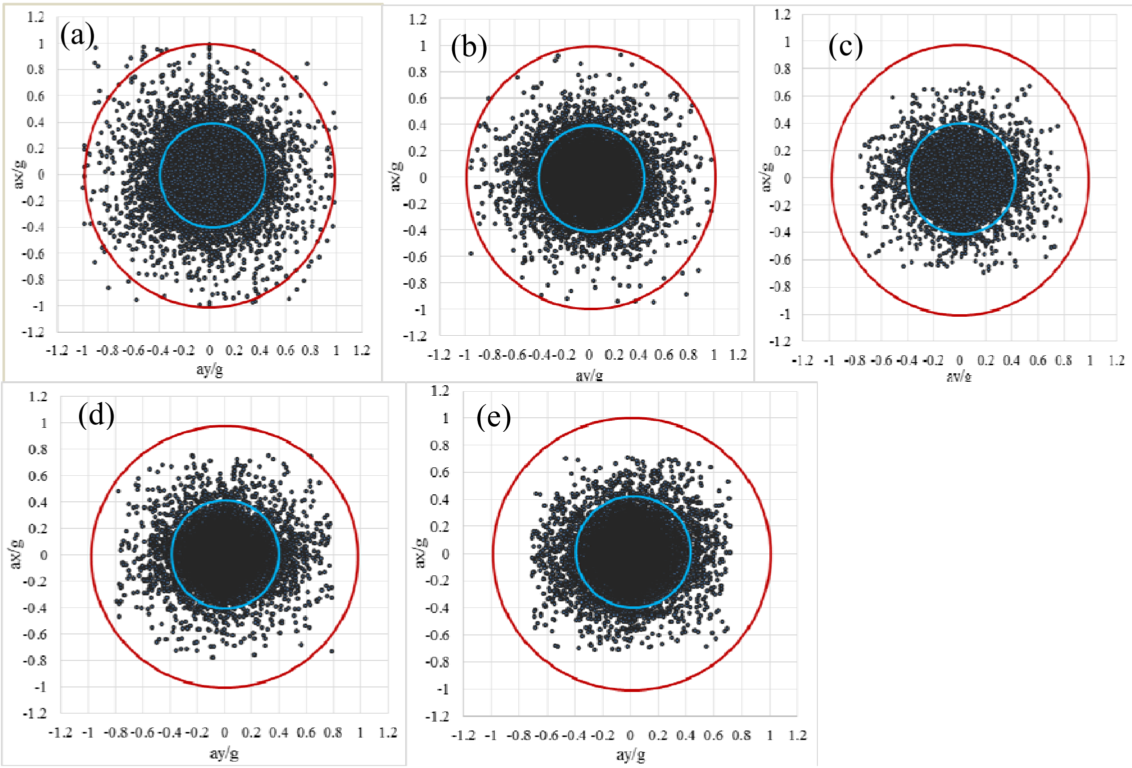


Figure 7. Normalized longitudinal and lateral acceleration (g-g plot) for (a) 2W (b) 3W (c) H-Back (d) Sedan & (e) SUV cars

As, both the longitudinal and lateral friction (μ_x and μ_y) occur in both the directions (x and y), the resultant force should be represented by the edge of the friction circle (μ) (refer Equation-1), assuming a hypothetical tire producing a maximum of only 1.0g of acceleration. If the driver needs to speed up with the turning movement simultaneously the maximum friction provided by his/her tires are limited to total 1.0g. The outer circle shown in the above figures are the maximum friction limit circle taken as 1.0g. The g-g diagram of all the vehicles indicates that the maximum data are scattered around the zero. The inside circle indicates the design friction limit of the road as per IRC:66, (1976) and IRC:86, (1983).

It can be observed that the g-g diagrams of all five type of vehicles produce interaction envelopes which are a small subset of the adherence circle or the friction circle of the tire. These envelopes represent "driver capability envelope" as mentioned by Biral et al.,(2005). In all cases, the driver takes a certain amount of risk while driving at higher than the design limits on plain terrain. The percentage of data points lies out of the design limit circle (inner circle) is very less i.e. below 1% for all type of vehicles (0.91% for 3W, 0.42% for H-Back, 0.49% for sedan and 0.52% for SUV cars) except motorized two-wheeler (2W) (i.e. 3.33%). There are nearly 1% vehicles takes a risk against skidding according to our design limit except for 2W. In the case of motorised 2W, the abrupt lateral manoeuvre of the vehicles are quite high in case of no-lane disciplined traffic due to their frequent lane change and overtaking manoeuvres. Hence the scattering of data is high in case of motorised 2W. Also, the motorised 3W have the higher weaving manoeuvre than the cars (H-Back, Sedan and SUV).

The g-g diagram can be viewed in more detail by plotting the lateral and longitudinal acceleration on three-dimensional plots for all five type of vehicles. The lateral and longitudinal acceleration data for each type of vehicles are grouped in six equal intervals of speed each 20 km/h ranging from zero to 100 km/h. The resulting plots show the lateral and longitudinal acceleration for different speed groups plotted along the z-axis (Figure-8).

It is observed that the g-g diagrams change their size with speed. At lower speed (0-20km/h) the g-g diagram covers a lesser area compared to the speed group of 20-40 km/h. In the case of lower to medium speed the size of the g-g diagram enlarges in all vehicle classes except motorised two wheelers and three wheeler. For all three type of cars, the size of g-g diagram shrinks with the further increase in speed. In all speed groups, the shape of the g-g diagram is approximately round. The shape and size of each g-g diagram changes with the driving capability of a different vehicle on plain terrain. The 3D plot of g-g diagram concludes that the driver capability envelop a function of operating speed of the driver for each type of vehicles.

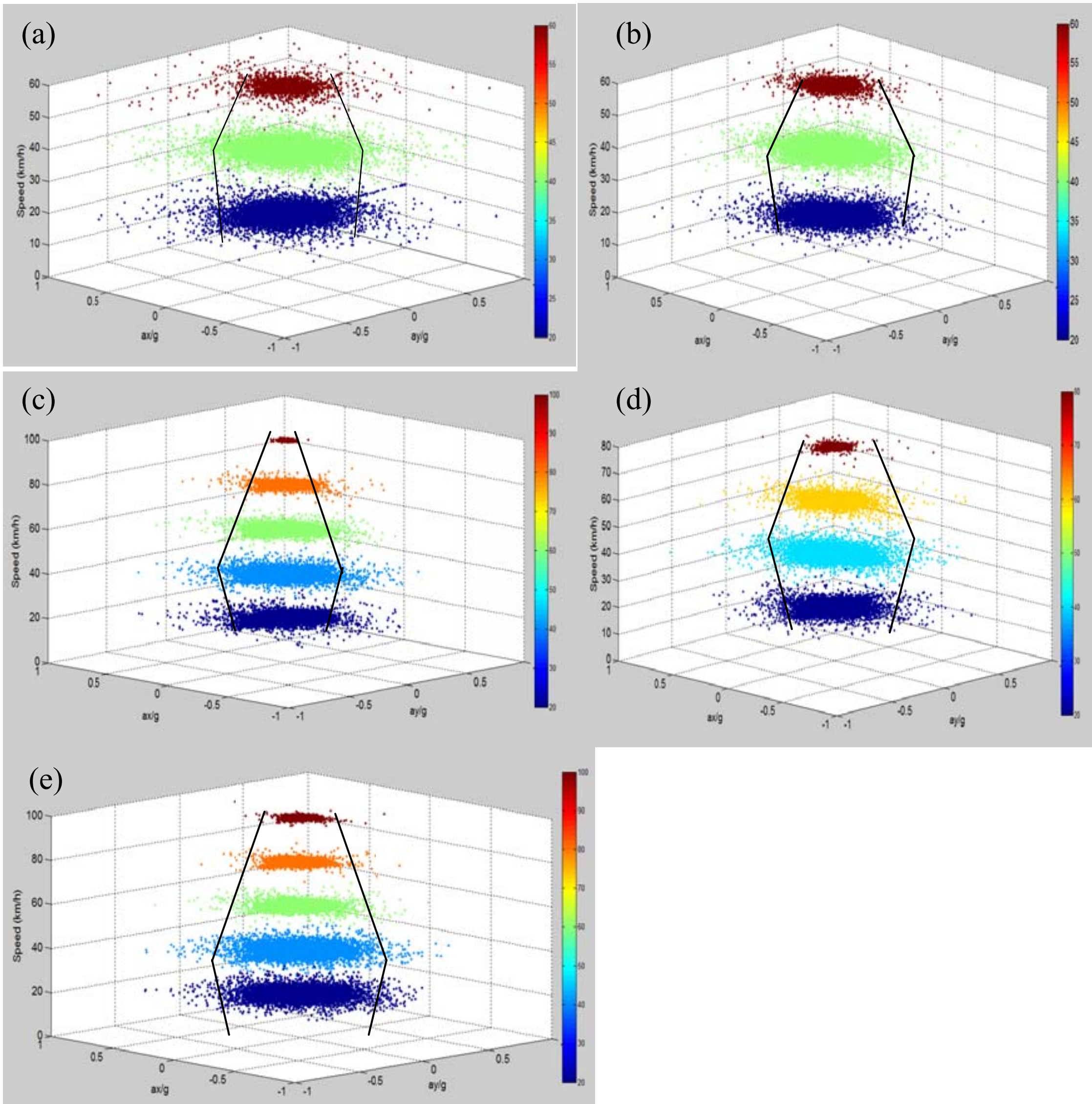


Figure 8. 3D Plot showing the Longitudinal and Lateral Acceleration Collected from field at different intervals of speed (a) 2W (b) 3W (c) H-Back (d) Sedan and (e) SUV Cars

3.3. g-g Diagram

The relationship between the acceleration vectors, $|\bar{a}|$,and operating speed of different vehicles is obtained in this section to represent the safe/unsafe driving behaviour of different vehicle types on mixed traffic stream by using the proposed approach of Eboli et al. (2016). The acceleration limit vs. speed curve by Eboli et al. (2016), shown in Figure-5 presents a clear drop down of the resultant acceleration ($\bar{a}$) with the increase in speed. In Indian traffic condition, the limit curve is obtained for the design criteria of the country as per IRC:66, (1976) and IRC:86, (1983) as mentioned in Section-2. The coefficient of lateral friction for curved road design is taken as 0.15, and the coefficient of longitudinal friction are presented in Table-1 as per the design guidelines.

Table 1. Values of Coefficient of Friction Limits Based on *(IRC:66 1976)*

Design Speed (km/h)	20	25	30	40	50	60	65	80	100
Coefficient of Friction (μ)	0.40	0.40	0.40	0.38	0.37	0.36	0.36	0.35	0.35

The resultant coefficient of friction (μ) is calculated based on the given coefficient of friction, as mentioned in Equation-1. The resultant acceleration limit ($\bar{a} = \mu . g$) is calculated for different design speed of vehicles based on the given coefficient of friction (depicted below in Figure-9).

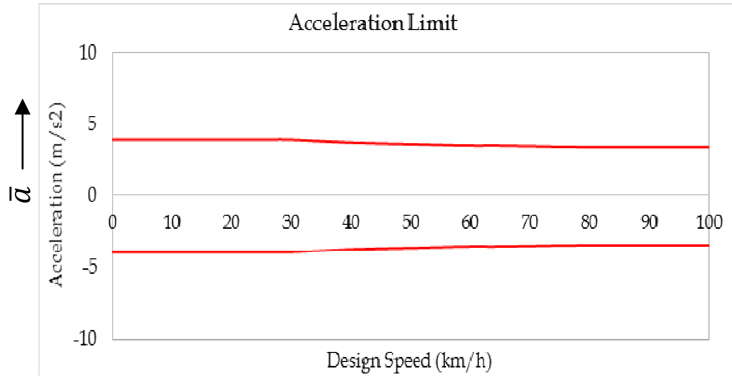


Figure 9. Safe Acceleration Limit Curve for Indian Roads

It can be observed that acceleration limit also decreases with the increase in design speed at medium to high operating speed. In the present study, the data was collected mainly in urban roads. The design speed of urban roads varies from 30 to 80 km/h (30 Km/h on Local streets, 50 km/h on Collector streets, 60 km/h onSub-arterial and 80 km/h on Arterial roads). The city wise scatter diagram for different vehicles are plotted to see the safe (least aggressive driving) and unsafe (most aggressive driving) condition. Figure-10 presents the city wise driving behaviour of all type of instrumented vehicles separately.

From the figures below, it has been observed that the points of resultant acceleration are scattered widely around mean in lower speed ranges i.e. below 40 km/h speed. Data points cross the limit curve frequently in the lowers speed ranges. This is due to the higher interaction with the adjacent vehicles, which leads to frequent lateral and overtaking manoeuvre of the vehicles in the no-lane disciplined mixed traffic conditions. Higher speeds are obtained by the drivers at relatively lower congested conditions, where the vehicles interaction are relativelylow. Hence, the driver mainly focuses on the longitudinal interaction and his/her reaction as regarding longitudinal acceleration and deceleration. Also, the driver feels unsafe to higher veering manoeuvre at higher speed conditions. Hence the lateral acceleration remains low at the higher operating speed of vehicles. The data points are clustered within ±2 m/s^2 acceleration limitafter 40 km/h speed in all vehicle cases, which is also below the acceleration limit curve obtained by Eboli et al.(2016). Only a very less percentage of data crosses the safe limit. It is also observed that, though the resultant acceleration limit (obtained from the design friction coefficient values) decreases with the increase in speed, there is a very less difference in the maximum resultant acceleration limit of zero speed and 100 km/h speed. These obtained limits are also higher compared the values obtained by Eboli et al.(2016).

From the scatter plot of resultant acceleration presented in Figure-10, one can observe that the percentage of data points outside the safety domain are very small. The 99% of data points lies within the safetydomain curve for all type of cars (H-Back, Sedan, and SUV), as shown in Table-2. However, for motorised two-wheeler and three-wheeler, the data lies outside the safety limit curve are more than 3% and 2% respectively. Though the longitudinal acceleration capability of cars is higher than that of motorised two-wheeler and three-wheeler, the resultant acceleration of both the vehicles ishighcompared to the cars. This is due to their higher lateral acceleration values compared to cars. This indicates that the lateral manoeuvre of two-wheeler and three-wheeler are high in all operating speed conditions.

Table 2. Percentage of external data points lies above the limit curve

City Name	*Vehicle Type*				
	2W	*3W*	*H-Back*	*Sedan*	*SUV*
Delhi	×	1.18	0.38	0.89	0.19
Kolkata	3.30	1.95	0.12	0.41	0.13
Bengaluru	1.41	2.04	1.28	1.69	1.28
Pune	8.39	1.30	0.49	0.12	0.66
Mumbai	×	0.46	×	0.49	0.43

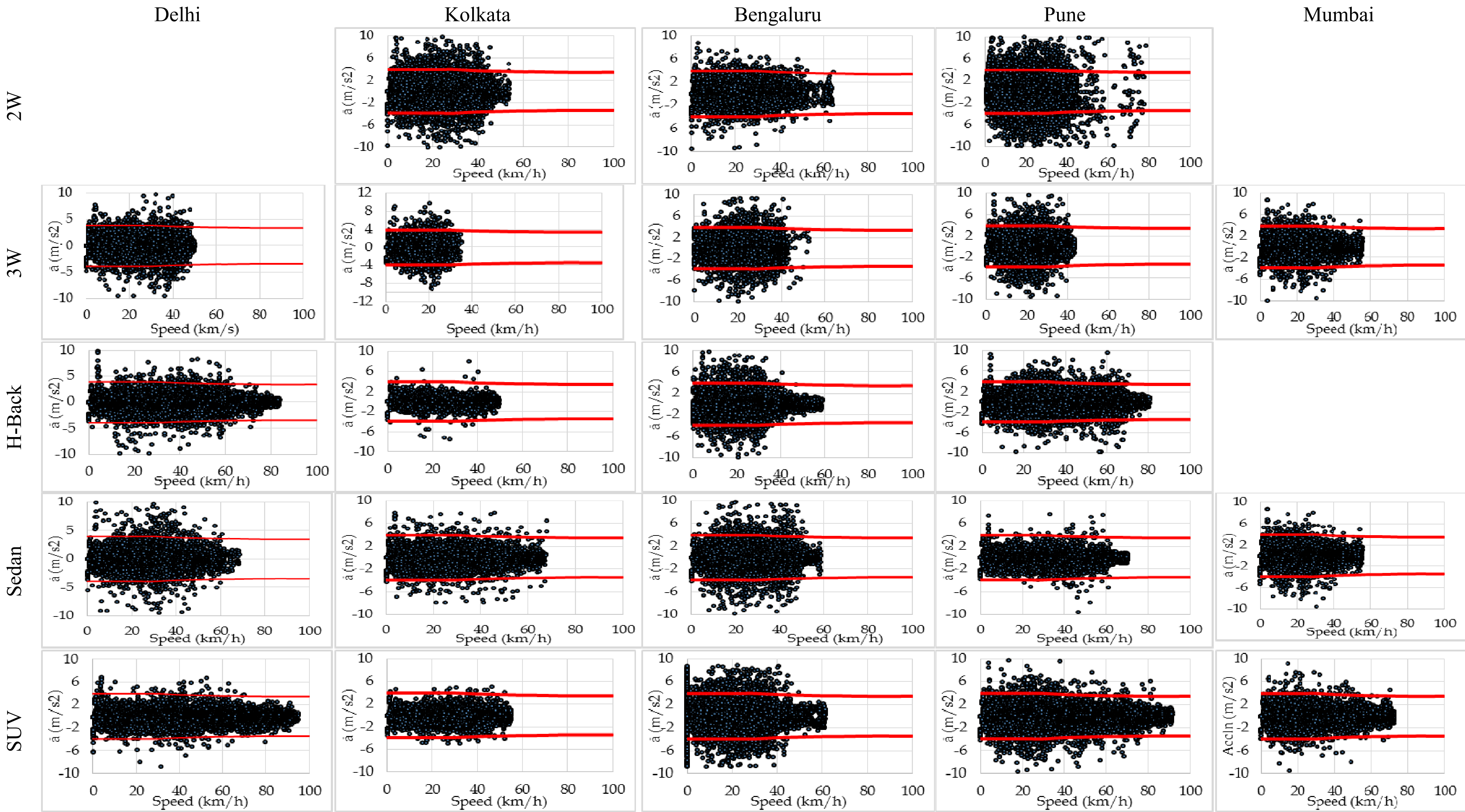


Figure 10. Scatter diagram of safe/unsafe behaviour of different vehicles on different city roads (2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan, and SUV are three categories of passenger cars)

To identify the safe or unsafe behaviour of the driver throughout travelled path (entire trajectory), the resultant acceleration ($\bar{a}$) trend with respect to the distance travelled of the vehicles are plotted. The safe/unsafe points in the entire road are identified by relevant exceeding limits. In case of unsafe behaviour of driver, the acceleration extends outside the safety domain. Therefore, such spatial plots helps in detailed analysis of risk driving conditions (the points where the drivers are taking risk while driving throughout the entire trajectory). Further, such plots highlight the design inconsistency of the road stretch using the indicator as the points where drivers' acceleration extends beyond safety domain. The acceleration trend with distance travelled are generated for different vehicles travelled in each city individually. Though the data collection trajectory is very long for each cities, only the first 5 km (5000 m) stretch are presented in Figure-11.

Figure-11 indicates that in the case of a motorisedtwo-wheeler, the acceleration exceeds the limit curve in most of the stretches of the total trajectory compared to other vehicle types. In the case of cars in all three cities (Delhi, Kolkata, and Mumbai), the points are more concentrated (follow the limit curve) and they exceed the safety domain at very few points. A safe and attentive driving behaviouris observed by the high-speed vehicles (all cars). It can be concluded that the randomness of the points reduces the size and capability of vehicles increases. The unsafety of the drivers is emphasised by the external points lying outside the limit curve indicating higher lateral/veering manoeuvre of vehicles. This veering manoeuvreindicates higher overtaking and frequent lane changing the behaviour of all types of vehicles which impliesmost unsafe behaviour of the driver. It can be observed from the study that the Bengaluru and Pune drivers are comparatively more aggressive than Delhi, Kolkata, and Mumbai. In the case of Bengaluru and Pune, the high-speed vehicles also show an unsafe condition at many road sections within the selected 5000 m path. However, the city wise acceleration presented in Figure-10 indicates that most of the data points lie within the safety envelope for all types of cars (less than 1% data lies outside the safety limit curve) except motorised two wheelers and three wheelers. This study can give a useful contribution regarding theimprovement of road safety. The safety domain defined is helpful in identifying those points/sections of the roadway where majority drivers show unsafe (risk taking) behaviour. Safety at such identified points/sections can be improved by providing necessary preventive measures or warning the drivers about it.

One of the main observation from the present study is that the unsafe behaviour of vehicles is mostly observed at lower to medium operating speed (i.e. below 30 km/h speed). This observation is due to the frequent interaction in the lateral and longitudinal direction of the subject vehicle in the urban roads with mixed, and no lane disciplined traffic. Hence, mostly the driver take the risk to pass or filter through the traffic at moderate speed conditions to overtake the slow moving vehicles. However, Eboli et al. (2016) observed that the higher lateral manoeuvreis observed at higher speeds (40-60 km/h). Due to the lane disciplined traffic, vehicles shift laterally only at the time of overtaking or lane changing (from high-speed lane to lower speed lanes or vice versa). This behaviouris observed during the moderate to the high speed of vehicles for lane based traffic i.e. 40 to 60 km/h.

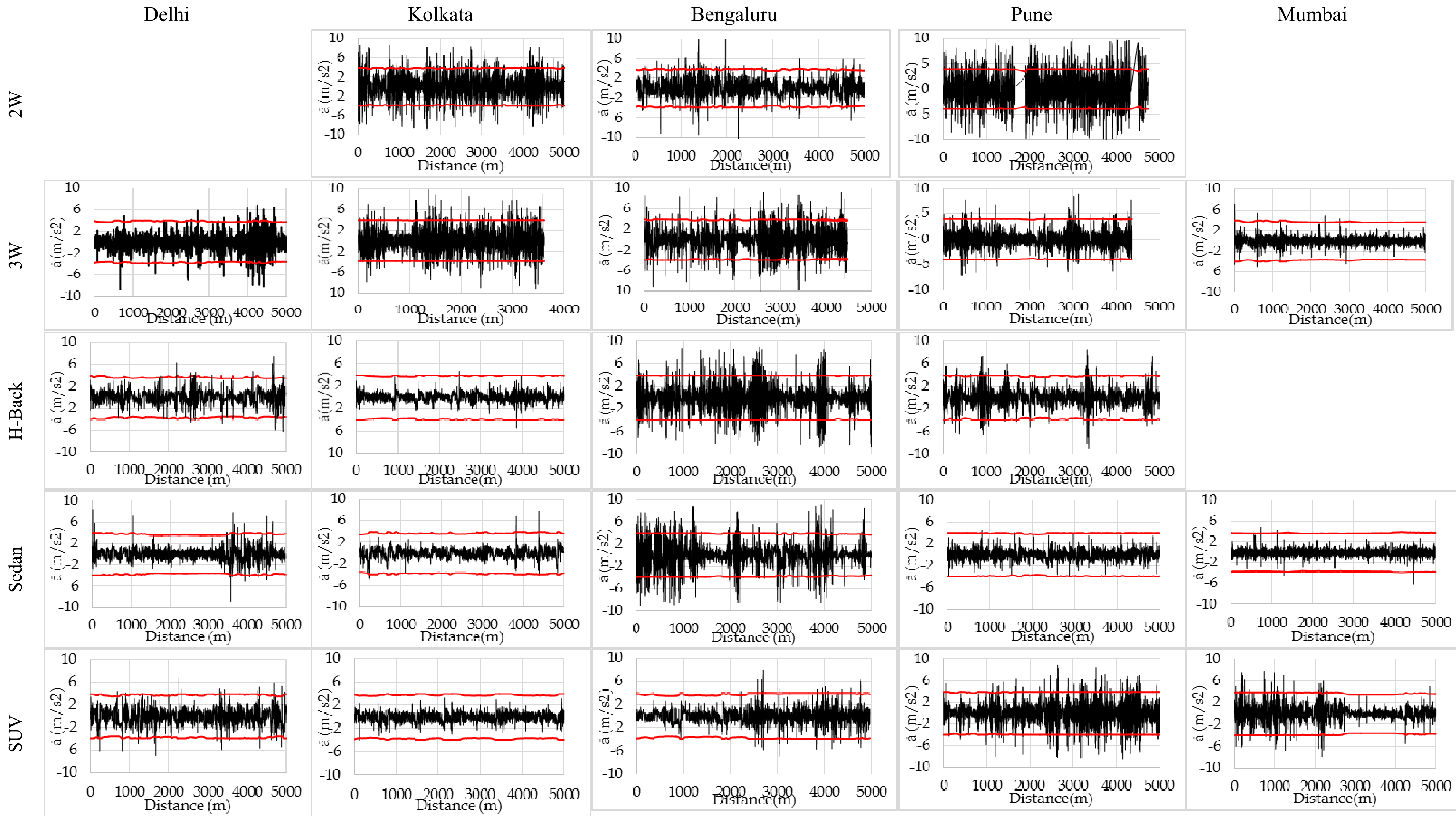


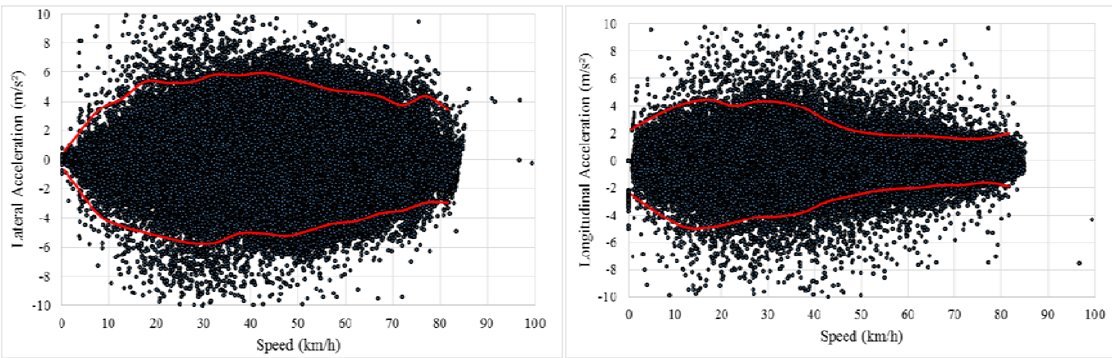
Figure 11. Acceleration trend in space for safe/unsafe behaviour of different vehicles on different cities (2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan and SUV are three categories of passenger cars)

4. Driving Behaviour Analysis on Plain Terrain

The extracted data for SUV car from both the hill road sections are analysed for the lateral and longitudinal acceleration first then the driving behaviour is analysed by plotting g-g diagram. The acceleration plot with distance travelled are plotted to analyse the drivers safe/unsafe driving based on the risk taken by the driver while driving as mentioned in Section-3. The driving behaviour of only SUV car is observedon hill roads, in the present study.

4.1. Acceleration Study

The longitudinal and lateral acceleration are plottedwith operating speed of SUV car (instrumented vehicle). The scatter plot for both longitudinal and lateral acceleration are depicted below with the 99% limit curve as presented in Section-3.1. It can be observed that the lateral acceleration is very low near zero speeds and it increases with increase in speed at lower to medium speed (i.e. <30 km/h) (refer Figure-12a). At around 30-40 km/h it attains a maximum value of lateral acceleration and decreases with the further increase in operating speed of cars (at higher speed i.e. > 40 km/h). However, the longitudinal acceleration is higher (±2 m/s^2) at lower speed conditions i.e. near zero speed, and it gradually increases with the increase in speed at lower speed conditions (i.e. <30km/h). It attains the maximum A/D at around 30-40 km/h speed. Afterwards, the 99% trend indicates a decreasing trend of longitudinal acceleration with the increase in speed. Thisindicates that at around 30-40 km/h speed the vehicles apply maximum A/D in normal driving conditions. It can also be observed that the in the case of hilly terrain roads the lateral acceleration gives higher values comparing to the longitudinal acceleration (a higher scattered data of lateral acceleration in Figure-12a). The range of 99 percentile lateral acceleration goes up to ±6 m/s^2, whereas the range of longitudinal acceleration lies within ±4 m/s^2. Hence, it can be concluded that the lateral manoeuvre of vehicles is higher in the case of hilly terrain, indicating the higher risk to vehicle stability. This observation is expected as the vehicle instability increases on curved sections.



(a) (b)

Figure 12. The acceleration trend with operating speed of SUV car at hill roads (a) Lateral Acceleration (b) Longitudinal Acceleration (99th percentile acceleration limit curve)

4.2. g-g Diagram

The driving behaviour of the instrumented test vehicles (SUV car) on the hilly roads are analysed by plotting the g-g plot as mentioned in the previous Section-3.2 (for plain terrain). To see the impact of operating speed of vehicles on driving behaviour, the g-g diagram is plotted in three dimensions (3D) with operating speed at z-axis.

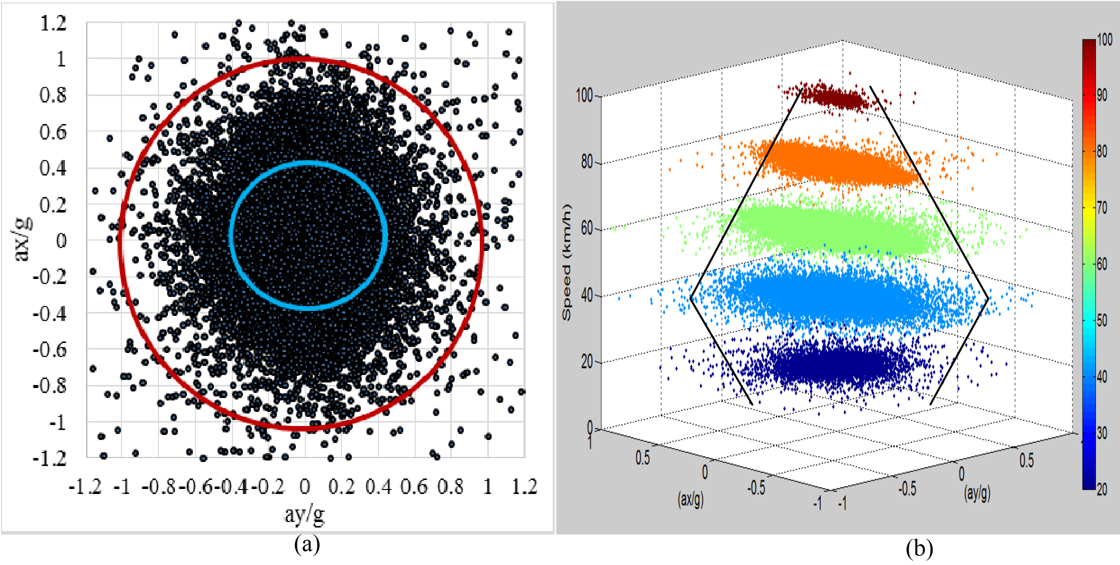


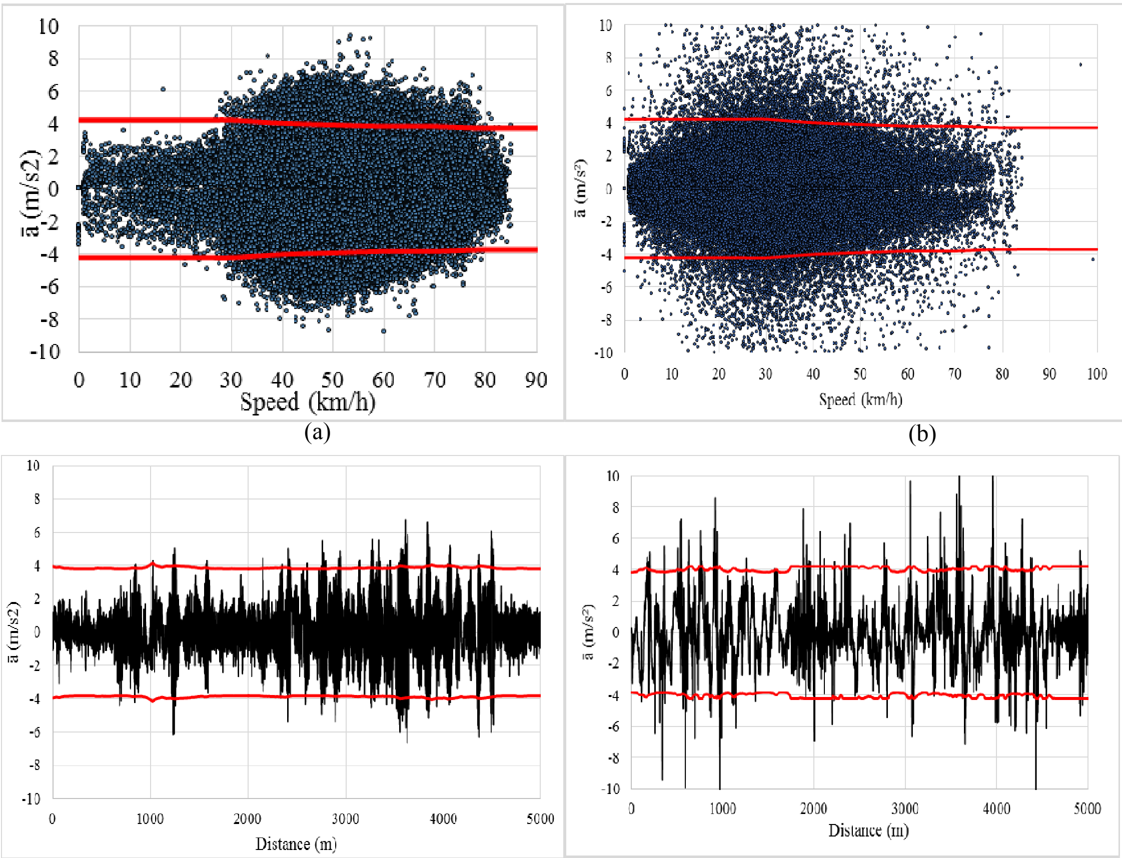
Figure 13. (a) Normalized longitudinal acceleration and lateral acceleration g-g plot and (b) Normalized Longitudinal and lateral acceleration with operating speed at z-axis (3D) plot of SUV car at hill road

It can be observed that the g-g plot can give a basic knowledge of vehicle-driverbehaviour of SUV cars at hill road sections. This plot is used to measure the overall capability of cars, the driver is using while driving.The g-g plot indicates that both the longitudinal manoeuvre (a_x/g) and lateral manoeuvre exceeds the design limit in case of hill road (i.e. around 5% data lies outside the inner friction circle. The outer circle shown in the above figure is the maximum friction limit circle assumed as 1.0g as described in case plain terrain (Section-3.2). The inside circle indicates the design friction limit of the road as per Indian Roads Congress guidelines IRC:66, (1976) and IRC:86, (1983).In case of hilly terrain roads also the g-g plot represents a circular shape indicating higher lateral and longitudinal acceleration/braking simultaneously (Figure-13a). According to IRC SP:23, (1993), the design speed limit of selected hill road is 50 km/h. However, it is observed that most of the driver exceeds the design speed limit and drives up to 90 km/h on the selected hill road. This might be one of the reasons for generating higher lateral and longitudinal A/D in case of hill road sections, indicating an aggressive driving behaviour of the vehicles.

From the 3D plot (Figure-13b), It can be observed that the friction circle increases with increase in speed at lower operating speeds (i.e. <40 km/h) and it decreases with increase in speed after 40 km/h (at higher operating speed). The maximum manoeuvreis observed at around 40 km/h speed. This is due to that the driver feels unsafe to manoeuvre laterally at higher operating speed on hill roads due to the inconsistency in driving behaviour.

4.3.Acceleration Limit Curve

In the present section, the safe or unsafe driving behaviour of the driver on both the hill roads is presented by plotting the acceleration limit curve as stated in Section-3.3. The limit curve in space (with distance travelled) are also plotted to see a driving behaviour in detail throughout the entire trajectories of both the roads (Guwahati-ShillongRoad& Siliguri-Gangtok Road). Here only a selected 5 km (5000 m) stretch is presented.



(c) (d)

Figure 14. (a) and (b) Scatter diagram of (ā) with safe/unsafe limit curve & (c) and (d) Acceleration trend with distance travelled for safe/unsafe behaviour of SUV car on Guwahati-shillongroad and Siliguri-Gangtok road respectively

It can be observed from Figure-14(a) and (b), that the resultant acceleration of the vehicles is low at operating speed below 30 km/h. In the case of Guwahati-Shillong road the road is a four-lane divided road and at most of the cases the vehicle was travelling at a free flow condition with a very less interaction with the surrounding traffic. Hence, the range of resultant acceleration is very less in this road at lower speed conditions. However, after 30 km/h, the resultant acceleration (ā) exceed the limit curve due to the higher lateral acceleration observed at curved roads on hilly terrain. In case of Siliguri-Gangtok road, the A/D or braking are higher due to the limited width of the road way (two lane bi-directional road). Hence a clearly increasing in acceleration trend is observed at a lower speed (<30 km/h) in this section. It is observed that more than 5% data (5.12 %) lies outside the limit curve throughout the entire trajectory, which is much higher than all vehicles in plain terrain.

The acceleration trend in space (i.e. with distance travelled) also indicates an unsafe or risky driving of the driver (Figure-14c and 14d). The cars exceed the limit curve at most of the stretch while driving, unlike the SUV cars at plain terrain roads of different cities. It can also be observed that the vehicle exceeds the design limit more frequently in Siliguri-Gangtok roads than the Guwahati-Shillong road (within the selected 5000m stretch). To know the driving behaviour in detail the impact of different horizontal and vertical curves on the driving behaviour need to be analysed further.

5. Conclusions

The dynamic parameters like speed, lateral and longitudinal acceleration can very well represent the driving behaviour of vehicles in a mixed non-lane disciplined traffic. The lateral as well as the longitudinal force coefficients, generated by the tire and road interaction while driving, are the key factors for vehicle stability and the driving safety. The proposed methodology can be used to characterise the driving style i.e. cautious or aggressive behaviour of the driver. The tire-forces model (g-g diagram) is used to implement safety margin concept.

The driving behaviour (adoption of safe or unsafe driving) is analysed by considering dynamic parameters like operating speed, lateral and longitudinal accelerations of the vehicles on both plain and hilly terrain roads. The proposed g-g diagram can easily demonstrate the safe or unsafe behaviour of a driver. The normalised accelerations with gravity (a_x/g and a_y/g) are plotted, and compared with the friction circle obtained from the design coefficient of friction. The friction points lie outside the safety envelop are considered as the risk-taking driving behaviourand is considered as unsafe. It is observed that in all cases the drivers of different vehicles adopts the safe driving in case of plain terrain roads (i.e. nearly 99% data lies within safe limit envelope "g-g diagram") except the motorised two wheelers (97%). It is observed that the motorisedtwo-wheelers are the most risk-taking drivers compared to cars in plain terrain. However, for SUV cars at Hill roads, the g-g diagram also represents a circular shape indicating higher lateral/longitudinal manoeuvre. The drivers take more risk to achieve their desired speed than the design limit at hill roads (more than 5% data lies outside the limit curve) indicating an aggressive driving.

The proposed diagram for resultant acceleration and design speed (safety domain curve), can easily demonstrate the safe or unsafe driving behaviour. The acceleration trend with the progressive (distance)interpret the exact locations of the trajectory where the driver experience sudden acceleration or deceleration (braking)additionally the points where lateral acceleration crosses the lateral threshold of the road design as stated by Eboli et al.(2016). It can be concluded from the present study that in all cases the drivers in plain terrain (different regions of the country) mostly drive within safe limit exceptmotorised two wheelers. Motorized two-wheelersmostlycross the safety domain very frequently. However, the SUV car in hilly terrain takes more risk than all vehicles in plainterrain while driving. This is due to the difference in road geometry. Hence, a brief analysis of driving behaviour on individual horizontal and the vertical curve are needed to see the impact of radius and gradient of the curve on lateral manoeuvre of the vehicles. This study can contribute to the road safetyimprovement. The defined safety domain is an important tool for finding the points on the trajectory, where the driving behaviour is safe/unsafe toinform him about his driving behaviour and produce the threshold of attention to take preventive measures.

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