Transportation Research Part C 68 (2016) 113–125

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Combining speed and acceleration to define car users' safe or unsafe driving behaviour

Laura Eboli, Gabriella Mazzulla *, Giuseppe Pungillo

University of Calabria, Department of Civil Engineering, P. Bucci, Cubo 46/B, 87036 Rende, CS, Italy

ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form 14 December 2015
Accepted 4 April 2016
Available online 9 April 2016

Keywords:
Road safety
Driving behaviour
Speed
Lateral and longitudinal accelerations
Real test on the road

ABSTRACT

Speed and acceleration describe the motion of a vehicle. Therefore, these parameters are fundamental to define the behaviour of a driver. To this aim, it is useful to analyse instantaneous and geo-referenced kinematic parameters of the vehicle recorded by real tests on the road.

Among all the available methods in the scientific literature, a way for characterizing driver behaviour is the g–g diagram, that shows the longitudinal and lateral accelerations on the *y* and *x*-axes, normalized with respect to gravity, recorded on a vehicle during a real test on the road. However, we retain that also speed has to be considered for characterizing drivers' behaviour, being acceleration and speed strictly interrelated. Starting from the g–g diagram, we propose a methodology which describes the relationship between lateral and longitudinal accelerations and speeds, and represents a tool to classify car drivers' behaviour as safe or unsafe. An app for smartphone allows the geo-referenced kinematic parameters of the vehicle to be detected. The experimental survey supporting the methodology was carried out on a rural two-lane road in Southern Italy.

1. Introduction

The motion of a vehicle is described by kinematic parameters like speed and acceleration, varying in time and space. Instantaneous and geo-referenced travelling kinematic parameters of the vehicle can be recorded by real tests on the road. The availability of this kind of data permits to track individual vehicles and to analyse the trajectories in order to verify drivers' behaviour, which includes all manoeuvres that a driver performs while driving, in safe or unsafe conditions. Different drivers have different driving behaviours: driver's personal characteristics and habits will affect their reaction when they face with a dangerous situation while driving (Chen et al., 2013). Traditionally, drivers were distinguished on the basis of their level of "aggressiveness" (e.g. Bonsall et al., 2005). An aggressive driver takes a driving behaviour characterized by high speed together with numerous and sudden changes of the instantaneous speed, which cause sudden accelerations and decelerations. The higher the speed variation, the greater the interactions among vehicles will be (Mehar et al., 2013). As a consequence, we can generally say that an aggressive driver has an "unsafe driving behaviour". On the contrary, some researchers have distinguished between two main categories of driver: "aggressive" or "cautious" (e.g. Wang et al., 2014). Cautious driver is often described also as "careful" (e.g. Taubman-Ben-Ari et al., 2004). A driver can be considered as cautious when he tries to maintain a constant moderate speed, avoiding sudden acceleration and braking, indicating that he has a "safe driving behaviour".

---

* Corresponding author.
E-mail addresses: laura.eboli@unical.it (L. Eboli), gabriella.mazzulla@unical.it (G. Mazzulla), giuseppe.pungillo@unical.it (G. Pungillo).

http://dx.doi.org/10.1016/j.trc.2016.04.002
0968-090X/

Numerous studies have focused on driving behaviour. A summary of these works is reported in Zeeman and Booysen (2013), who highlighted that the main differences between these studies are in the specific application area and the sensing employed method. According to this literature review, research focus has recently shifted from visual monitoring to the use of vehicle-mounted motion sensors. Motion sensors, such as accelerometers and gyroscopes, allow vehicle's speed, lateral, longitudinal and vertical accelerations, and instantaneous vehicle positions to be measured and recorded. Motion sensors are becoming increasingly important due to their simplicity, robustness and low cost.

Among all the available methods in the scientific literature, a way for characterizing driver behaviour is the g–g diagram that shows the longitudinal and lateral accelerations on the *y* and *x*-axes, normalized with respect to gravity, recorded on a vehicle during a real test on the road (Hisaoka et al., 1999). As emphasized by Da Lio et al. (2005), this diagram represents a very effective way to characterize vehicle–driver performance, because longitudinal and lateral acceleration values can be seen as the synthesis between the vehicle dynamics and the driving behaviour selected according to driver's motion perception and the risk level he/she accepts. However, it is necessary to consider also that speed is important too to characterize drivers' behaviour, and speed and accelerations are strictly interrelated.

The aim of this paper is just to analyse the relationship between lateral and longitudinal acceleration and speed in order to have a tool to classify car drivers behaviour. We distinguish drivers' behaviour from safe to unsafe driving conditions, according to the instantaneous values of accelerations and speeds recorded by real tests on the road. The parameters were surveyed through smartphones with satellite-based Global Positioning System (GPS) device, and specifically by using an app for smartphone which allows the geo-referenced kinematic parameters of the vehicle to be detected. The experimental survey was carried out on a rural two-lane road in Southern Italy.

After this brief introduction, we propose a literature review of the studies that analysed the relationship between acceleration and speed, and between friction and speed, being these parameters the elements considered for the development of our proposed methodology for analysing driving behaviour. After literature review, the methodology is described, together with the experimental survey conducted for validating it. The paper ends with a brief conclusive section.

2. Literature review

2.1. Relationship between acceleration and speed

Speed and acceleration rates are primary parameters in the estimation of road safety conditions. Since 1930 some studies have focused their attention on the relationship between speed and accelerations during the vehicle motion. Specifically, a paper proposed by Goebelbecker and Uzgiris (1998) refers about a series of filed tests carried out in 1930s and 1940s to determine the safe speed on curves. Some relationships between lateral acceleration and speed were found, indicating that the lateral acceleration decreases when speed increases. The results established levels of lateral acceleration to which drivers of heavy trucks experienced some discomfort; it was found that drivers are more tolerant of lateral acceleration at slower speeds than at higher speed (AASHTO, 1984).

Also in recent years, several researchers have focused on the relationship between speed and accelerations. As an example, Reymond et al. (2001) proposed a driving behaviour model which takes into account the drivers' estimation of both maximal lateral acceleration and predictable steering corrections, based on their driving style and experience. They showed that in curves maximum lateral acceleration quadratically decreases with driving speed. Vehicle speed and lateral acceleration were recorded on a test truck by driving a real vehicle equipped with a set of high-precision accelerometers, gyrometers, and optical velocity sensors. A pattern of lateral accelerations was also tested by driving a simulator.

Wang et al. (2004) collected field data to analyse acceleration rates of different vehicles using GPS, and proposed two new polynomial models developed for driver acceleration behaviour for turning manoeuvres versus straight manoeuvre acceleration from a stopped condition. Specifically, the model formulations were quadratic relationship between acceleration and speed, proving that acceleration decreases with driving speed also at all way stop controlled intersections.

Da Lio et al. (2005) found relationships between longitudinal acceleration and speed, and lateral acceleration and speed. By using empirical data, they observed that longitudinal acceleration varies with speed by following two phases: in a first phase longitudinal acceleration is constant with speed, and in a second phase it linearly decreases with speed. Differently, lateral acceleration increases from low to medium speeds, and then linearly decreases with speed as well.

Brooks (2012) found that also during overtaking manoeuvres in rural roads vehicles decrease their acceleration when speed increases; the link deduced from experimental data is a linear relationship. Acceleration characteristics were manually observed.

Zeeman and Booysen (2013) proposed a model that combines speed and acceleration to detect reckless driving in public transport. This model considers only the lateral accelerations to create an erratic driving detection model. The authors consider a lateral threshold based on design standards and a longitudinal threshold as a rate of deceleration based on literature studies.

Mehar et al. (2013) measured maximum and average acceleration at different speeds for different types of vehicles, from a standstill condition to a higher speed. According to their analysis, the average acceleration is found to exponentially decrease when speed increases, whereas the maximum acceleration linearly decreases with speed.

Xu et al. (2015) showed that lateral acceleration depends on driving speed and trajectory curvatures. They analysed the change laws for the lateral acceleration over the speed based on experimental data measured on twelve highways with different design speeds and topographies; they found that lateral acceleration is negatively related to speed. Based on the data gathered from three road types, an aggregated scatter diagram showed that lateral acceleration decreases as speed increases.

A deep examination of the literature review allows some matters to be identified: relationship between acceleration and speed was analysed for various traffic and road conditions, by proving that vehicles decrease their acceleration when speed increases, whichever mathematical formulation was proposed (constant, two-phase, linear-decreasing, or polynomial acceleration model). However, two main critical issues emerged: (1) relationship between acceleration and speed was analysed in the previous studies by considering only a component of the acceleration (longitudinal acceleration vs speed or lateral acceleration vs speed) but no studies analysed both longitudinal and lateral components of accelerations varying with speed; (2) most of the previous studies developed different acceleration models based on outdated and limited data, so their conclusions may not be applicable for the current vehicle fleet and drivers.

As a consequence, in order to fill these gaps it is necessary to propose more accurate relationship between acceleration and speed, which have to be validated by means of a large amount of data regarding instantaneous values of accelerations and speeds recorded by real tests on the road.

2.2. Relationship between friction and speed

During the vehicle motion, driving dynamics deals with the physical laws as regards the vehicle's properties and road characteristics. According to these laws, different forces are transmitted between the tyres and the road pavement due to friction. The maximum transmissible friction force depends on the characteristics of both tyre and road pavement, and on the presence of any substance on the contact area between tyre and pavement. Among all the forces, the longitudinal (tangential) and lateral (radial) ones are the most important.

Friction force plays a significant role in driving safety; it primarily depends on the friction coefficient and on the vehicle weight (Lamm et al., 1999). A distribution of the skidding friction factor related to speed was developed by Wehner (1965), based on the measurement of different wet road surfaces with standardized tyres. In any condition there is a decreasing trend of this factor as a function of speed. Also Reimpell and Sponagel (1988) found a similar distribution of the skidding value in relation to speed for wet road surface and different surface types or texture. In Germany, the skid resistance evaluation background for wet road surface was introduced by Lamm and Herring in 1980. Evaluations of dry and snowy/icy road surfaces were completed by 1992 (Lamm et al., 1999). Lamm and Herring found an equation based on 95th percentile distribution curves as threshold values of skid resistance, meaning that 95% of roads would lie above the threshold.

Relationship between longitudinal or radial side friction and speed deduced by other authors from experimental data can be usefully adopted for estimating the maximum permissible friction factor as a function of speed in different traffic and road conditions.

Excessive values of acceleration can cause loss of vehicle control, that is an unsafe driving condition. In order to define better this limit condition, the adherence force counteracting the skid vehicle has to be expressed as a function of speed. Then, a more accurate estimate of the relationship between friction and speed allows a more accurate estimate of the safety limit to be obtained.

3. Method

As mentioned in the literature review, most of the studies analysed driving behaviour based on one or two kinematic parameters among lateral and longitudinal accelerations, and speed. However, real driving scenarios are often very complex, demanding simultaneous lateral and longitudinal control. As known to the authors, there are no studies that propose the simultaneous use of lateral and longitudinal accelerations, and speed for analysing driving behaviour. On the contrary, our methodology aims to define a road safety domain based on all the three kinematic parameters.

In the following, we describe in detail the proposed methodology, which is based on the dynamic equilibrium of the vehicle. First of all, we consider some restrictions on the basis hypotheses, with the aim to simplify the methodology. However, the adopted assumptions can be considered as a conservative approach because they work to road safety's advantage. The first restriction is about the friction coefficient: we assume that friction factor has a constant value coinciding with the minimum of the longitudinal and the radial friction factor, so that the ellipse of adherence becomes a circle as better explained in the following. The second restriction relates to the hypothesis that there is no superelevation in curve: as a consequence, the stabilizing component of the vehicle weight which is opposite to the centrifugal force is not considered.

In order to explain in a more detailed manner the adopted methodology, we can consider that, during its travel, and especially in a circular curve, a vehicle is subject to an $\bar{a}$ acceleration vector in the horizontal plane, where $\bar{a}$ has a_{long} (longitudinal acceleration in the same direction of the motion) and a_{lat} (lateral acceleration in the direction transverse to the direction of the motion) components.

The $\bar{a}$'s modulus is (Eq. (1)):

$$|\bar{a}| = \sqrt{a_{lat}^2 + a_{long}^2} \tag{1}$$

According to the second law of Newton, the vehicle is subject to a F_S stimulate force, that has modulus equal to (Eq. (2)):

$$F_S = m \cdot |\bar{a}| \tag{2}$$

where m is the vehicle mass.

F_S is balanced by a centripetal force depending on the side friction between tyre and road pavement, and by the mass of the vehicle. Therefore, there is an F_R resistant force, as in the Eq. (3):

$$F_R = W \cdot \mu \tag{3}$$

where μ is the coefficient of side friction, and W is the vehicle weight. So, the resistant force can be expressed as in Eq. (4):

$$F_R = m \cdot g \cdot \mu \tag{4}$$

As above mentioned, a conservative assumption is to not consider the superelevation, that is a cross incline that has the task of reducing the centrifugal acceleration. Under this assumption, when the vehicle is in condition of limit equilibrium, F_S is equal to $F_{R.}$ More precisely, we can obtain three driving conditions:

(a) if $F_S < F_R$, we have a safe driving condition
(b) if $F_S = F_R$, we have a limit driving condition
(c) if $F_S > F_R$, we have an unsafe driving condition.

The tyre force saturation is a physical constraint, which limits vehicle dynamics and manoeuvrability. Only the trajectories that do not demand forces over the tyre limits are feasible.

Therefore, it is necessary to analyse better the limit condition ($F_S = F_R$) in order to determine the threshold values of acceleration, as a function of speed, that delimit the safe driving condition from the unsafe condition.

Starting from the limit condition, and considering the expressions in Eqs. (2) and (4) we obtain (Eq. (5)):

$$m \cdot |\bar{a}| = m \cdot g \cdot \mu \tag{5}$$

and then (Eq. (6)):

$$|\bar{a}| = g \cdot \mu \tag{6}$$

which can be written as (Eq. (7)):

$$\sqrt{a_{lat}^2 + a_{long}^2} = g \cdot \mu \tag{7}$$

Squaring both members, we obtain (Eq. (8)):

$$a_{lat}^2 + a_{long}^2 = (g \cdot \mu)^2 \tag{8}$$

Eq. (8) represents, in the (a_{lat}, a_{long}) plane, a circumference of radius $g \cdot \mu$ centred at the origin, where lateral acceleration is plotted on the horizontal axis and longitudinal acceleration on the vertical axis.

The circumference represents the borderline between safe and unsafe driving conditions. In safety conditions, each point should not be outside the limits. In practice, when there are both lateral and longitudinal accelerations, the resultant acceleration should not exceed an upper limit that could lead to the vehicle sliding off the road.

As shown in Eq. (8) these margins of road safety relate to the side friction (μ) between tyres and road surface. This coefficient varies with speed and meteorological conditions that influence the state of the contact surfaces.

The side friction is conventionally broken down into two components: longitudinal side friction (μ_x), in the same direction of the motion, and lateral side friction (μ_y), perpendicular to the direction of the motion.

As relationship between longitudinal friction factor and speed, we assume a formulation derived from literature review and reported in Lamm et al. (1999), which calculates the maximum friction value in longitudinal direction under dry pavement condition for rural road (Eq. (9)):

$$\mu_{xmax} = 0.214 \cdot \left(\frac{V}{100}\right)^2 - 0.640 \cdot \left(\frac{V}{100}\right) + 0.615 \tag{9}$$

where V is the speed expressed in kilometres per hour.

According to Lamm (Lamm et al., 1999), the relationship between μ_x and μ_y can be assumed as (Eq. (10)):

$$\mu_y = 0.925 \cdot \mu_x \tag{10}$$

The maximum permissible friction side in radial direction cannot be measured. By combining formula (9) with formula (10), the maximum friction value can be calculated as follows (Eq. (11)):

$$\mu_{ymax} = 0.198 \cdot \left(\frac{V}{100}\right)^2 - 0.592 \cdot \left(\frac{V}{100}\right) + 0.569 \tag{11}$$

By considering longitudinal side friction (μ_x), in the same direction of motion, and lateral side friction (μ_y), perpendicular to the direction of motion, the following ellipse equation is valid (Eq. (12)), which is well-known as “ellipse of adherence”:

$$\left(\frac{\mu_y}{\mu_{ymax}}\right)^2 + \left(\frac{\mu_x}{\mu_{xmax}}\right)^2 \leqslant 1 \tag{12}$$

where (Fig. 1):

- μ_x and μ_y represent the components of the vector of "global" side friction $\overline{\mu}$;
- μ_x is the available tangential friction factor in the longitudinal direction;
- μ_y is the available radial friction factor in the lateral direction;
- μ_{xmax} is the maximum (permissible) tangential friction factor in the longitudinal direction;
- μ_{ymax} is the maximum (permissible) radial friction factor in the lateral direction.

Because we are interested in the limit value of μ (μ_{max}), which has to be replaced in the Eq. (8) to obtain the acceleration limit value $\bar{a}$, it is more convenient (and a conservative assumption too) to approximate the ellipse of adherence with a circle of radius μ_{ymax}. In this way we can obtain the same modulus of global side friction for each direction (Fig. 2).

According to this assumption, all points of the border are at the same distance from the origin of the axes (equal to μ_{ymax}); then, in Eq. (8) we can consider just a value as a function of speed, instead of a mathematical expression.

By replacing Eq. (11) in Eq. (7) we obtain the limit curve of $\bar{a}$ acceleration as a function of speed (Eq. (13)):

$$\sqrt{a_{lat}^2 + a_{long}^2} = g \cdot \left[0.198 \cdot \left(\frac{V}{100}\right)^2 - 0.592 \cdot \left(\frac{V}{100}\right) + 0.569\right] \tag{13}$$

or

$$|\bar{a}| = g \cdot \left[0.198 \cdot \left(\frac{V}{100}\right)^2 - 0.592 \cdot \left(\frac{V}{100}\right) + 0.569\right] \tag{14}$$

In the (V, $\bar{a}$) plane, we have a decreasing trend of $\bar{a}$ as a function of V speed. The relationship is quadratic (Fig. 3). In the (V, a_{lat}, a_{long}) space, we have a circle (a_{lat}, a_{long}) that reduces its radius when speed increases. The points that are outside the curve represent unsafe driving conditions while those inside represent conditions of safety for the driver.

As we can see in Fig. 3, $\bar{a}$ values close to ±6 m/s^2 are safe for speed near to zero. On the other hand, at speed close to 100 km/h, threshold values are about ±2 m/s^2 (one third of the previous values).

4. Experimental surveys

We conducted an experimental survey with the specific aim of confirming that real acceleration and speed points recorded by real tests on the road follow the proposed function shown in Fig. 3.

In order to confirm the shape of the domain, about 400 tests covering about 5000 km were made. All the experimental surveys were conducted in a good weather condition, that is under dry road pavement conditions, in weekdays, during daytime and out-of-pick hours in order to have no influence of traffic flow. Survey involved 13 drivers having different driving behaviour. Each driver covered more times the same path, except two drivers who drove on two different paths. The average path length is about 12 km. Each path was repeatedly run by driver in order to collect the instantaneous speed and acceleration along the pattern. To this aim, GPS-enabled smartphones were used; by means of a free app named Torque, the kinematic values were recorded with a frequency of 1 hertz, together with the instantaneous vehicle position (latitude and longitude).

The use of GPS-enabled mobile phones represents a low-cost opportunity for collecting instantaneous vehicle speeds and other dynamic characteristics. However, the accuracy of the collected data have to be established. In recent years, many researchers have argued on this subject. As an example, since 2010 some authors have evaluated speed measurements accuracy from GPS-enabled mobile phones by proving the high accuracy in position and velocity measurements provided by GPS units (Herrera et al., 2010). More recently, in order to account for uncertainty in probe speeds and position as affected by satellite signal interruption, some authors carried out experiments to obtain speed profiles using various GPS-enabled smartphones and a more sophisticated sensor system (high frequency V-Box) as a benchmark (Guido et al., 2014). An additional test was carried out comparing smartphone speed profiles with aggregate speed profiles obtained from a fixed radar detector. The smartphone devices were found to closely replicate the speed profiles obtained from a fixed detector station. In addition, they prove that probe estimates obtained from smartphones provide accurate real-time traffic data for safety analysis.

During the tests more than 400,000 instantaneous values of vehicle positioning have been registered. Scatter diagrams in the (V, $\bar{a}$) plane of the recorded values confirm the negative correlation between acceleration and speed represented in Fig. 3.

As a reference example, the behaviour of few drivers is analysed. But specifically, we report more accurately the results emerging from real tests conducted by one driver numbered as n.1. The survey interested a part of the Italian National road n.107 (S.S. 107) which is a rural two-lane road 138 km long connecting the Tyrrhenian with the Ionian coast of the Calabria region, in Southern Italy. The high flow, combined with heavy rains and frequent snowfalls, has gradually increased the dangerousness of the road, especially in some tortuous and difficult parts. In fact, the road is in the list of the ten most dangerous roads of Italy, occupying the 7th place (ACI, 2007). The analysed road segment is 5 km long and it is between km 20 and km

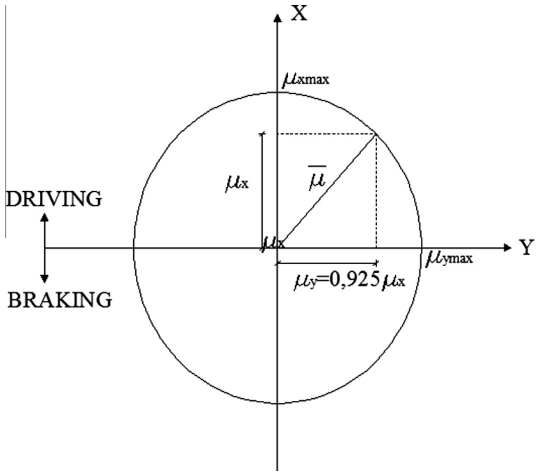

Fig. 1. Borderline between safe and unsafe driving conditions using an ellipse of adherence. μ_{ymax} is the maximum (permissible) radial friction factor in the lateral direction.

25. The segment has a roadway and two lanes, one for each direction, having a width of 3.5 m each. The driver made 34 real driving tests on the same path. 9154 instantaneous values vehicle positioning (latitude and longitude) were registered, with an average value of 278 points per survey.

The experimental analysis seems to confirm the theoretical domain. Figs. 4 and 5 show the extreme behaviour of the driver in question: the safest (or the least aggressive) and the most unsafe (or the most aggressive). Specifically, Fig. 4 shows an aggressive driving behaviour while Fig. 5 a cautious driving behaviour.

In Fig. 4 the points are more scattered, and unsafety of the driver is accentuated by a considerable number of external points (62 out of 225). It is observed that the maximum speeds are around 100 km/h, over the legal limit (90 km/h). The major part of external points is placed in the interval of speed between 90 and 100 km/h. It seems that the driver becomes more aggressive when he/she travels at high speeds, denting a very unsafe behaviour.

In Fig. 5 the points are more concentrated than in Fig. 4. They follow the trend of the curve and only in some cases are outside the safety domain (19 points out of 316). A cautious behaviour is also confirmed by the maximum speed that does not exceed 80 km/h, and therefore it is under the legal limit for the considered road section.

We can observe that in the interval of speed from 45 to 65 km/h almost all points fall into a range of acceleration from -2 and 2 m/s^2, which is considerably below the borderline. This proves a very safe behaviour of the driver.

Comparing the two different situations, we can observe that the differences of the percentage of points outside the safety domain is significant: from 6% for the safe behaviour to 28% for the unsafe behaviour. Also speed values present relevant differences, being 80 and 100 km/h the maximum values reached in the two different contexts.

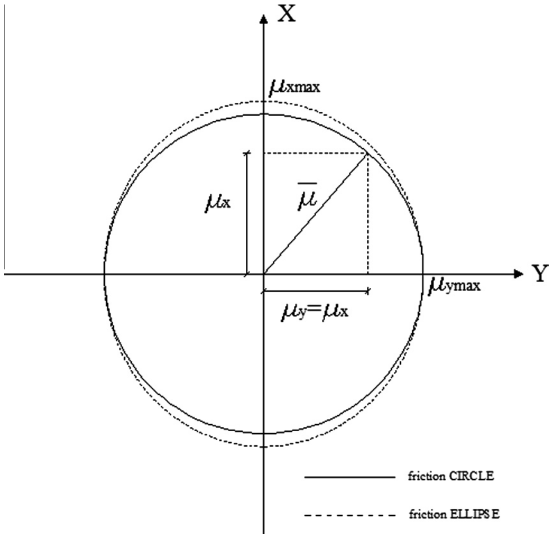

Fig. 2. Borderline between safe and unsafe driving conditions using both circle and ellipse of adherence.

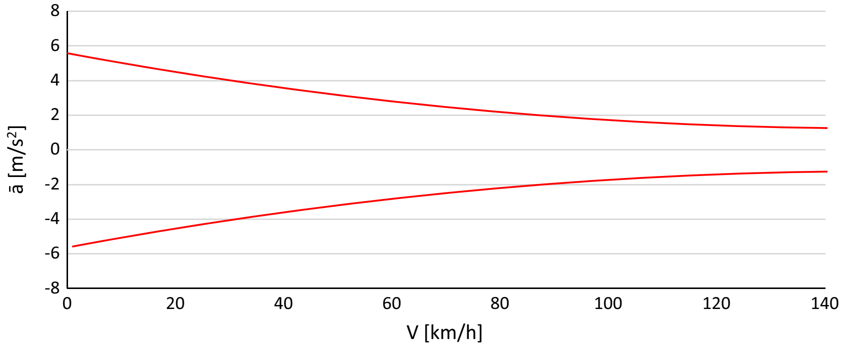

Fig. 3. Borderline between safe and unsafe driving conditions in the (V, $\bar{a}$) plane.

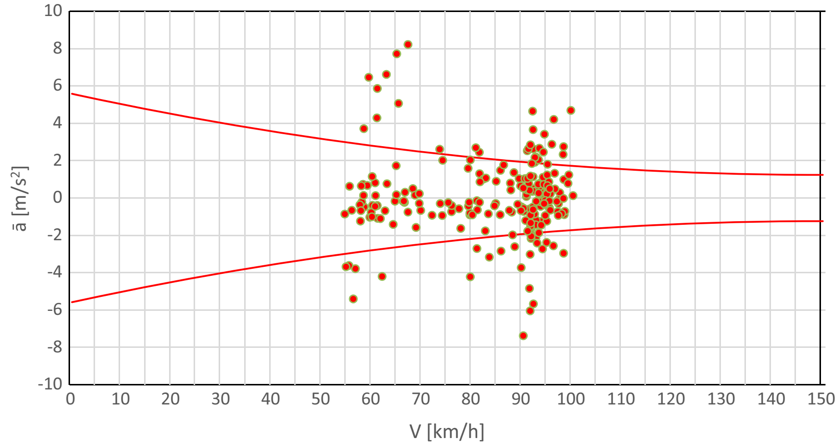

Fig. 4. Scatter diagram for the most unsafe behaviour (driver n.1).

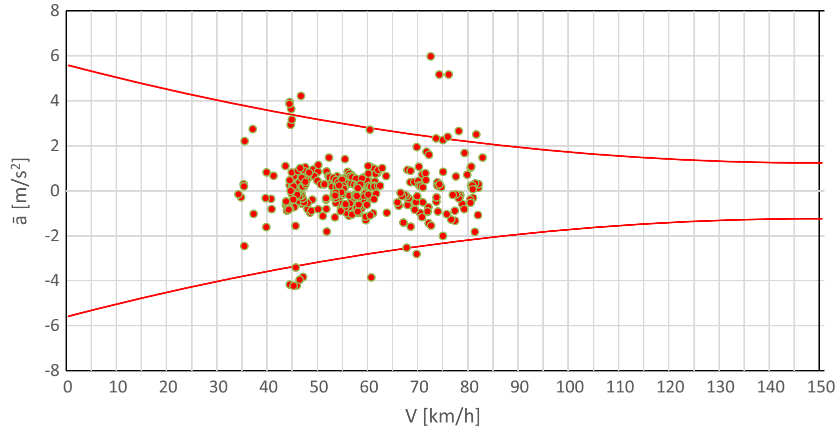

Fig. 5. Scatter diagram for the safest behaviour (driver n.1).

Figs. 6 and 7 show acceleration trend in space, for the most unsafe and the safest behaviour, respectively. We can see the trend of the $\bar{a}$ acceleration vector as a function of the progressive, and where this vector exceeds the limits that are a function of speed as previously mentioned.

As we can see from the trend registered for the unsafe behaviour (Fig. 6), acceleration goes out of the safety domain in more stretches of the path; there is a specific stretch (from 2500 to 3500 m) characterized by a relevant exceeding the limits. On the contrary, safe behaviour (Fig. 7) shows few points out of the safety domain.

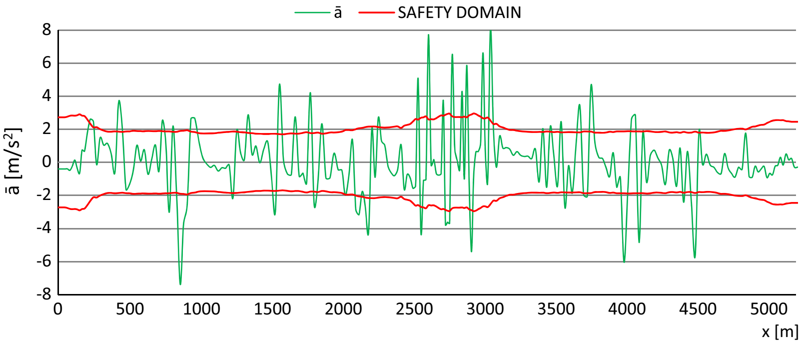

Fig. 6. Acceleration trend in space for the most unsafe behaviour (driver n.1).

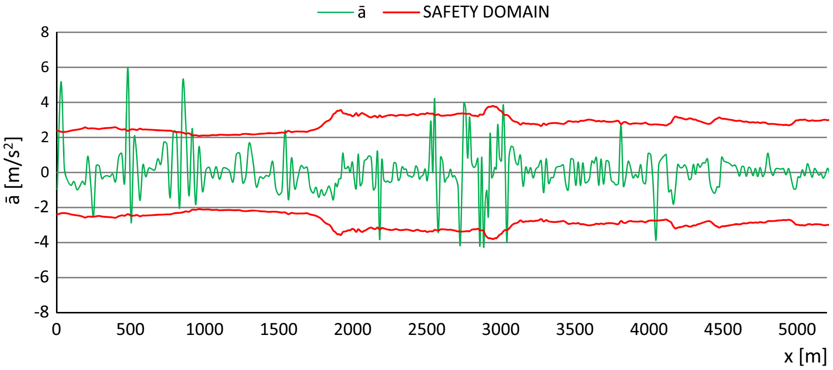

Fig. 7. Acceleration trend in space for the safest behaviour (driver n.1).

Because the measured points are geo-referenced we can know at what point of the path driver is unsafe. Fig. 8 represents a survey concerning the most unsafe behaviour, while Fig. 9 is representative of the safest behaviour. In both cases we can see where driver is safe (the [1]green points) or unsafe (the red points). As expected, there are many more red points for the case of the aggressive behaviour. We can observe an unsafe condition both for the aggressive and the cautious behaviour at specific road sections (50, 500, 1000, from 2500 to 3500 m). This evidence could be due to the presence of road design inconsistence, and not only to driver behaviour (Eboli et al., in press).

In order to test more appropriately the methodology transferability and robustness, we briefly introduce also the results of other drivers riding other roads, and named driver n.2 and driver n.3.

Driver n.2 rode also along a part of S.S. 107, from km 29 to km 20, on a road segment 9 km long. The driver made 29 real driving tests on the same path. 21,108 instantaneous values of vehicle positioning (latitude and longitude) were registered, with an average value of 728 points per survey.

Figs. 10 and 11 show the scatter diagrams for the most unsafe and the safest driver behaviour, respectively. We can see that unsafety of the driver is accentuated by several external points (65 out of 514); it is observed that the maximum speeds are around 95 km/h, over the legal limit (90 km/h). In Fig. 11 the points are more concentrated than in Fig. 10. They follow the trend of the curve and only in some cases they are outside the safety domain (17 points out of 601). A cautious behaviour is also confirmed by the maximum speed, which does not exceed 80 km/h, and therefore it is under the legal limit for the considered road section.

Figs. 12 and 13 show acceleration trend in space, for the most unsafe and the safest behaviour, respectively. As we can see from the trend registered for the unsafe behaviour (Fig. 12), acceleration goes out of the safety domain in more stretches of the path; there is a specific stretch (from 6500 to 7500 m) characterized by a relevant exceeding the limits. By comparing Figs. 12 and 13, we can see also that there is a stretch of the path (from 2000 to 2500 m) where high values of deceleration are recorded; specifically, there are three spots corresponding with road intersections where design inconsistency emerged. In this section, driver behaviour is maybe influenced by road geometric conditions.

Driver n.3 rode also along a rural two-lane road that is a part of the Italian national road n.107bis (S.S. 107bis). The analysed road segment is 8 km long and it is between km 173 and km 181. The segment has a roadway and two lanes, one for each direction, and each one has a width of 3.25 m. The driver made 28 real driving tests on the same path. 13,250

---

[1] For interpretation of colour in Figs. 8 and 9, the reader is referred to the web version of this article.

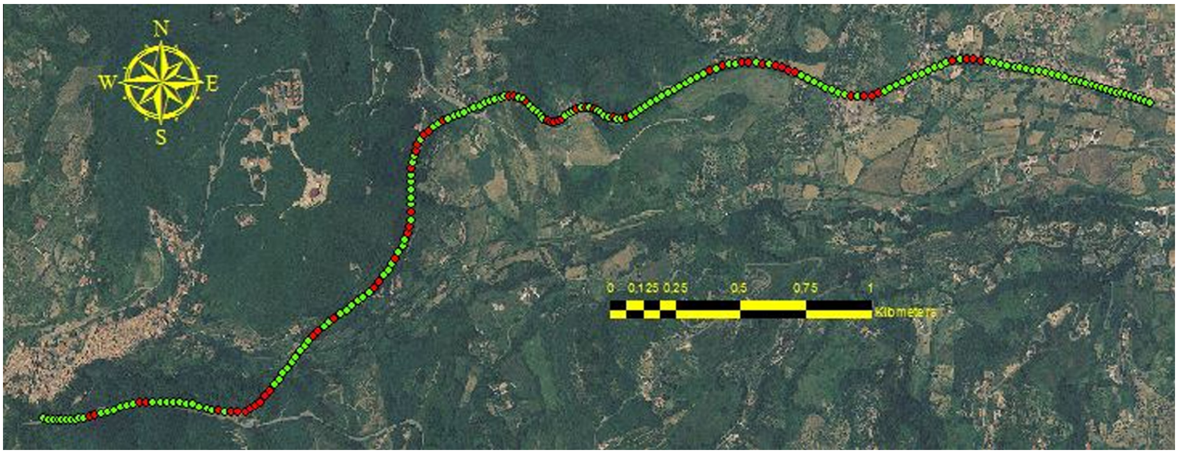

Fig. 8. Representation of the survey on the map for the most unsafe behaviour (driver n.1).

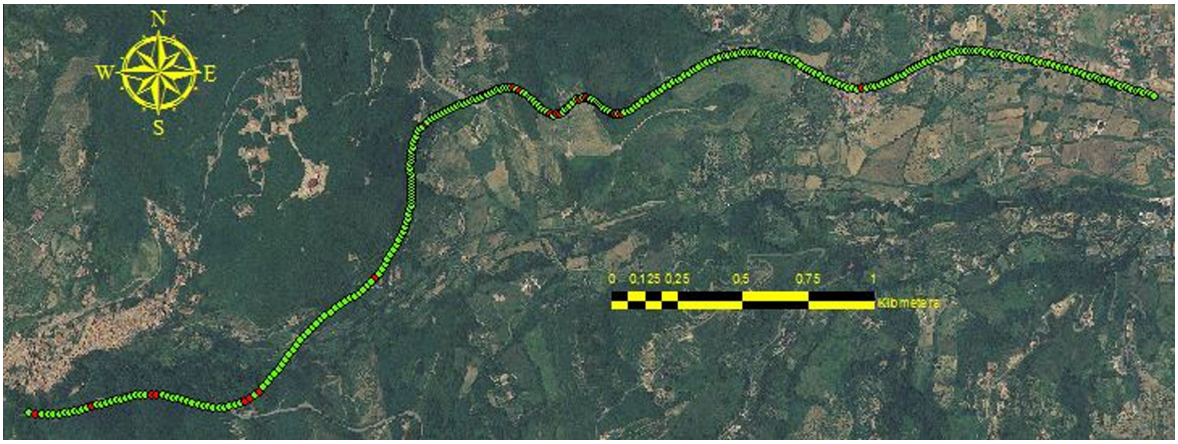

Fig. 9. Representation of the survey on the map for the safest behaviour (driver n.1).

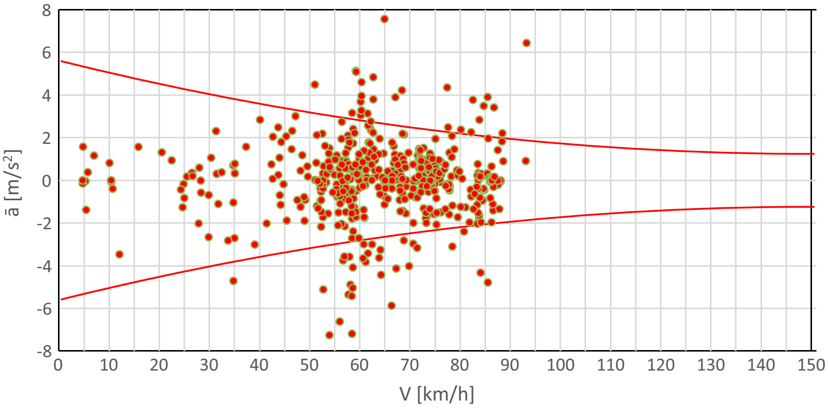

Fig. 10. Scatter diagram for the most unsafe behaviour (driver n.2).

instantaneous values of vehicle positioning (latitude and longitude) were registered, with an average value of 473 points per survey.

Figs. 14 and 15 show the scatter diagrams for the most unsafe and the safest driver behaviour, respectively. Also in this case, unsafety of the driver is accentuated by a considerable number of external points (51 out of 394); it is observed that the

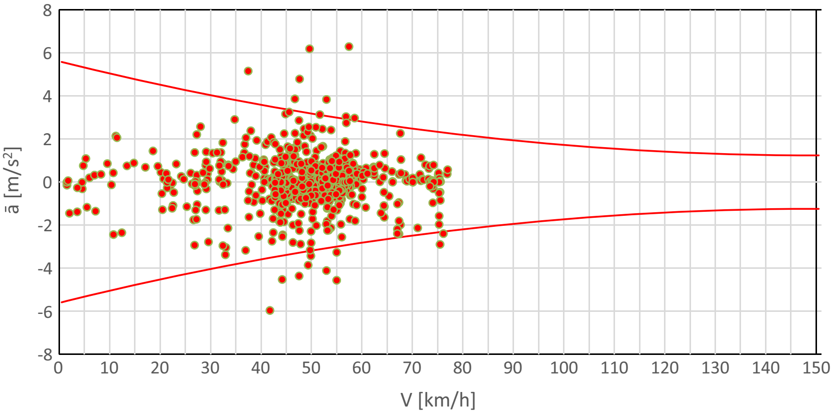

Fig. 11. Scatter diagram for the safest behaviour (driver n.2).

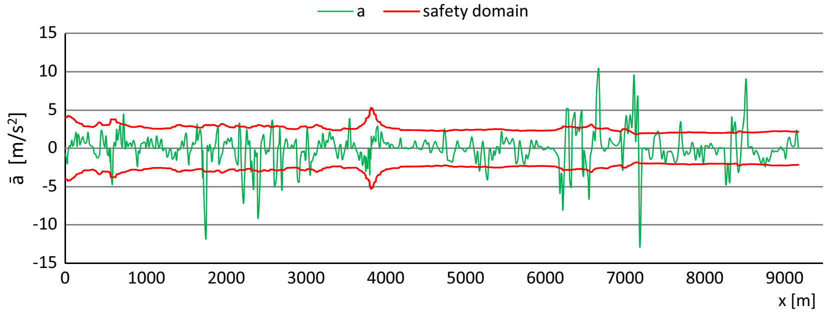

Fig. 12. Acceleration trend in space for the most unsafe behaviour (driver n.2).

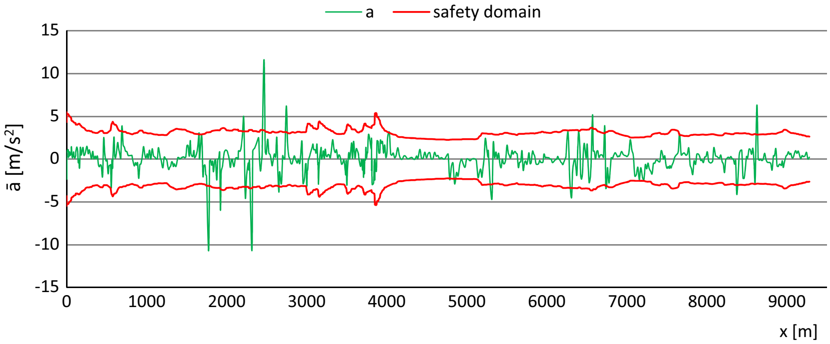

Fig. 13. Acceleration trend in space for the safest behaviour (driver n.2).

maximum speeds are over 95 km/h, well over the legal limit (70 km/h). When driver n.3 has a safe behaviour, the recorded points follow very strictly the trend of the curve, and there is only one point, out of 740, outside the safety domain. A cautious behaviour is also confirmed by the maximum speeds, which do not exceed 55 km/h, and therefore they are under the legal limit for the considered road section.

Figs. 16 and 17 show acceleration trend in space for the most unsafe and the safest behaviour, respectively. A strong difference between the two behaviours is evident, and it is highlighted by the safety domain in Fig. 17, which is very distant from instantaneous values of acceleration.

5. Conclusions

In this work we proposed a methodology for analysing driving behaviour by considering kinematic parameters such as speed and longitudinal and lateral accelerations as the elements that can best explain if driver adopts a safe driving or

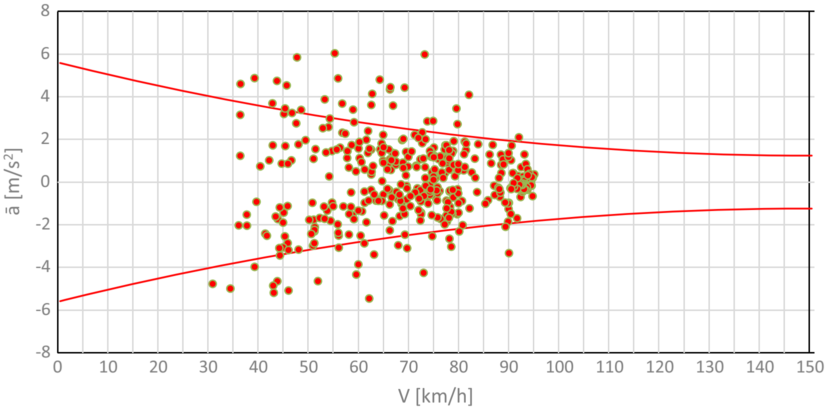

Fig. 14. Scatter diagram for the most unsafe behaviour (driver n.3).

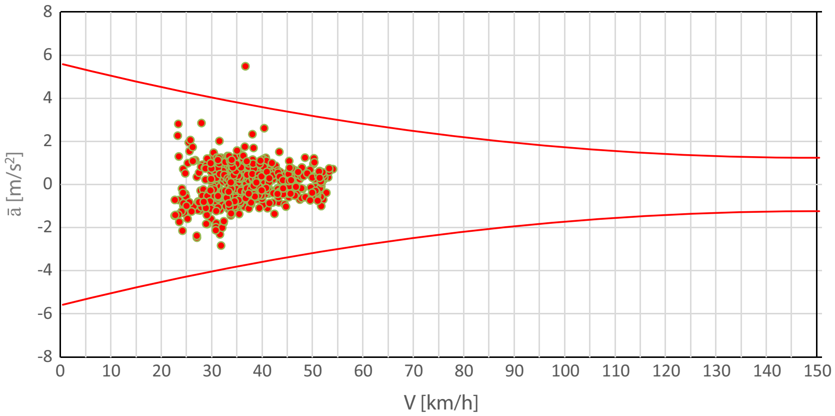

Fig. 15. Scatter diagram for the safest behaviour (driver n.3).

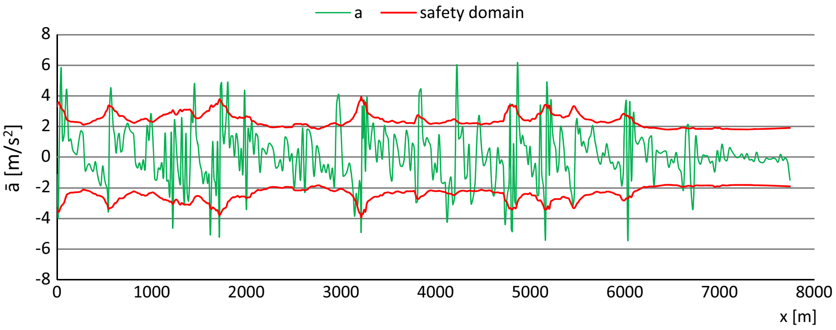

Fig. 16. Acceleration trend in space for the most unsafe behaviour (driver n.3).

not. More specifically, starting from the well-known g–g diagram, we propose a diagram which easily shows the safe or unsafe behaviour of a driver. By effecting real tests on a rural two-lane road in Southern Italy we recorded real values of accelerations and speeds by using an app for smartphone which allows the geo-referenced kinematic parameters of the vehicle to be detected. Thanks to the collected real data we were able to define a safety domain inside which driver is in safe conditions; on the contrary, if the kinematic parameters are out of the domain we can consider driving behaviour as unsafe. The results obtained by the experimentation proposed in this preliminary work confirm our theoretical hypotheses, which we are going to validate better by analysing the large amount of data collected through the whole survey.

We retain that our research can give a contribution in terms of improvement of road safety. In fact, the safety domain defined in this work is very useful for finding those points of the roadway where the driver is unsafe, in order to give

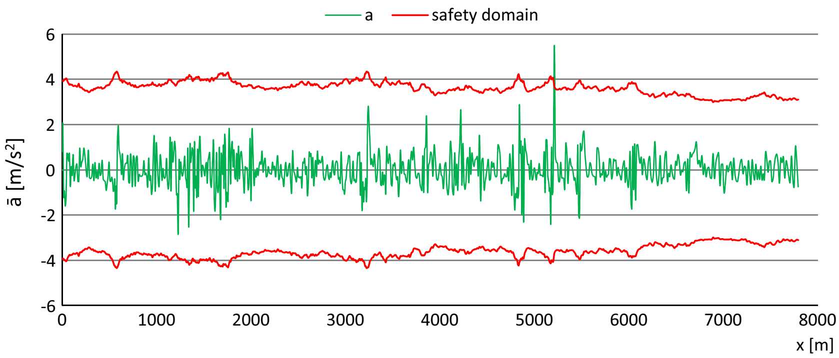

Fig. 17. Acceleration trend in space for the safest behaviour (driver n.3).

him information about his behaviour, let him raise the threshold of attention and let him take preventative measures. As an example, through ITS, by an acoustic signal we can inform the driver, in real time, that he/she is out of the safety domain.

The proposed method could represent also a tool to obtain an overall judgment on the style of driving, according to the percentage of points out of the borderline, and for classifying driving style from a cautious to an aggressive behaviour.

We retain that the proposed methodology has some advantages with respect other literature studies because of the simultaneous use of both longitudinal and lateral acceleration, and also speed. On the contrary, as an example, the methodology proposed by Zeeman and Booysen (2013) takes into account only the lateral acceleration. Differently from other methodologies, through our method we can identify places where the driver does not hold a uniform speed or where he/she experiences sudden acceleration or braking as well as the points where lateral acceleration is above the road design lateral threshold.

Future development of the research will surely consist in a deeper analysis of all the 400 tests in order to establish a percentage of points out of the safety domain defining the border between an aggressive and a cautious driving behaviour, and different levels of driving aggressiveness. Experimental data will be analysed by taking into account also contexts that are different from rural roads, such as urban roads and highways. Another point of interest is the road pavement conditions. At this stage of the research, we focused particularly on dry pavement conditions, that is the road condition under which most of the traffic accidents occurred (Lamm and Choueiri, 1991). It would be interesting to analyse also road pavement under wet and slippery conditions.

Acknowledgements

The authors are grateful to the anonymous referees for their precious comments. They desire to thank also the drivers who voluntarily made the real tests on the road.

References

Automobile Club Italia (ACI), 2007. Localizzazione degli incidenti stradali 2006.

American Association of State Highway and Transportation Officials, 1984. Policy on Geometric Design of Rural Highways and Streets.

Bonsall, P., Liu, R., Young, W., 2005. Modelling safety-related driving behaviour-impact of parameter values. Transport. Res. Part A 39, 25–44.

Brooks, R.M., 2012. Acceleration characteristics of vehicles in rural Pennsylvania. Int. J. Res. Rev. Appl. Sci. 12 (3), 449–453.

Chen, S.W., Fang, C.Y., Ting Tien, C., 2013. Driving behaviour modelling system based on graph construction. Transport. Res. Part C 26, 314–330.

Da Lio, M., Biral, F., Bertolazzi, E., 2005. Combining safety margins and user preferences into a driving criterion for optimal control-based computation of reference manoeuvres for an ADAS of the next generation. In: Intelligent Vehicles Symposium, Las Vegas, USA, June 6–8.

Guido, G., Gallelli, V., Saccomanno, F., Vitale, A., Rogano, D., Festa, D., 2014. Treating uncertainty in the estimation of speed from smartphone traffic probes. Transport. Res. Part C 47, 100–112.

Herrera, J.C., Work, D.B., Herring, R., Ban, X., Jacobson, Q., Bayen, A., 2010. Evaluation of traffic data obtained via GPS-enabled mobile phones: the Mobile Century field experiment. Transport. Res. Part C 18, 568–583.

Eboli, L., Guido, G., Mazzulla, G., Pungillo, G., in press. Experimental relationships between operating speeds of successive road design elements in two-lane rural highways. Transport. http://dx.doi.org/10.3846/16484142.2015.1110831.

Goebelbecker, J.M., Uzgiris, S.C., 1998. Margin of safety for heavy trucks on curves. Saf. Bull. 7 (2).

Hisaoka, Y., Yamamoto, M., Okada, A., 1999. Closed-loop analysis of vehicle behavior during braking in a turn. JSAE Rev. 20, 537–542.

Lamm, R., Choueiri, E.M., 1991. Traffic safety on two continents. A ten-year analysis of human and vehicular involvements. VTI Rapport 372A, Part 1.

Lamm, R., Psarianos, B., Mailaender, T., 1999. Highway Design and Traffic Safety Engineering Handbook. McGraw-Hill.

Mehar, A., Chandra, S., Velmurugan, S., 2013. Speed and acceleration characteristics of different types of vehicles on multi-lane highways. Eur. Transport 55, 1–12.

Reimpell, J., Sponagel, P., 1988. Vehicle-Technique: Tires and Wheels. Vogel Publishing House, Wurzburg, Germany.

Reymond, G., Kemeny, A., Droulez, J., Berthoz, A., 2001. Role of lateral acceleration in curve driving: driver model and experiments on a real vehicle and a driving simulator. Hum. Factors 43 (3), 483–495.

Taubman-Ben-Ari, O., Mikulincer, M., Gillath, O., 2004. The multidimensional driving style inventory. Scale construct and validation. Accid. Anal. Prevent. 36, 323–332.

Wang, C.A., Fu, R.A., Peng, J.S.B., Mao, J.A., 2014. Driving style classification method for lane change warning system. J. Transport. Syst. Eng. Inform. Technol. 14 (3), 187–193.

Wang, J., Dixon, K.K, Li, H., Ogle, J., 2004. Normal acceleration behaviors of passenger vehicles starting from rest at all way stop controlled intersections. Transportation Research Record No 1883, TRB, National Research Council, pp. 158–166.

Wehner, B., 1965. Results of skid resistance measurement and traffic safety. Road Interstate 8, 261–268.

Xu, J., Yang, K., Shao, Y.M., Lu, G.Y., 2015. An Experimental Study on Lateral Acceleration of Cars in Different Environments in Sichuan, Southwest China. Discrete Dyn. Nat. Soc., 1–16

Zeeman, A.S., Booysen, M.J., 2013. Combining speed and acceleration to detect reckless driving in the informal public transport industry. In: Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems, The Hague, The Netherlands, October 6–9.