(Review Paper)

A Review of Safety Guidelines for Vehicles in Floodwaters

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Abstract: The development of guidelines for the design and analysis of street drainage systems to ensure safety of pedestrians and vehicles is an issue of fundamental importance. To prevent pedestrians and vehicles from being swept away during flooding events, the up to date guidelines are recommended in Australian Rainfall and Runoff (AR&R, 2011) report. These guidelines are based on the upper bounds on both depth and velocity; and the constant limiting velocity × depth ($v \cdot y$) functions derived from the earlier works (1967-1993) associated with the stability of old-fashioned vehicles (*static condition*). The AR&R (2011) guideline does not include the assessment of the studies on modern vehicles (*static*) which were published very close or after its release (2010-2017). However, as a result of considerable modifications in the chassis design since those former investigations, several issues concerning stability of modern vehicles in floodwaters have been raised. Herein this paper ponders on both the limit functions highlighted in those earlier and recent works. Further, the reported works have highlighted that the studies performed on vehicles in the past were limited to static condition, therefore in this paper an attempt has been made to address hydrodynamic response of a non-static vehicle endangered by floodwaters. Thus, the algorithms of the hydrodynamic studies for the non-static vehicle into safe stability limits will be presented, under the consideration of few modified parameters, which involves the rolling resistance generated at vehicle tires, drag impact at vehicle's front end and driving force caused by vehicle engine.

Keywords: safety guidelines; floodwaters; stability limits; limiting thresholds; buoyancy depth; static and non-static vehicles

1. Introduction

Flooding is the most frequent and expensive natural hazard worldwide [1], [2] and [3]. The transportation structures are highly exposed and unprotected to flood danger because of its significant size [4]. Flood-based fatalities are increasingly related to people perishing in vehicles mainly due to stability failure while crossing the flooded roads [5], [6] and [7]. On the subject of flood hazards relating to vehicle movement, rivers overflowing onto the floodplains can seriously disrupt the transportation system which could lead to significant risks to vehicles which are moving or parked along floodplains. At times, the intensity of floodwater flows could wash away the flooded vehicles which could damage the infrastructure or even cause fatalities by means of collision [8]. It is therefore vital to investigate the hydraulic behavior and hazard conditions of vehicles on floodplains during floods to reduce or ideally minimize such possible disastrous consequences [9] and [10].

Hazard has many components including stability of vehicles, people and structures in floodwaters, flood awareness of the population, evacuation difficulty, etc. Concerning stability of vehicles in floodwaters, these standards are given in the form of buoyancy depth and velocity × depth ($v{\cdot}y$) functions, which are available nearly in all the councils within the major urban centers. These regulations rely on the facts highlighted in the published sources, namely the experimental investigations highlighted in work of Bonham and Hattersley (1967) and Gordon and Stone (1973); and the theoretical analysis performed on the variety of vehicles in the early 1990's by Keller and Mitsch (1993) [11]. Though, it is unlikely that the stability regions proposed for the variety of old-fashioned static cars available in that era could be directly relevant to the modern static cars [12], because when it comes to vehicles, features like weight, aerodynamic design, ground clearance and sealing capacity determines vehicle stability in floodwaters [13]. By far, the Australian Rainfall and Runoff (AR&R, 2011) guideline compiles the up to date criterion regarding stability of vehicles in floodwaters. It does not include the assessment of subsequent studies performed on modern static vehicles, namely Teo *et al.* (2010) [14], Xia *et al.* (2011) [15], Shu *et al.* (2011) [16], Oshikawa *et al.* (2011) [17], Toda *et al.* (2013) [18], Xia *et al.* (2013) [19], Xia *et al.* (2014) [20] and Martínez-Gomariz *et al.* (2017) [21], which were published very close or after its release.

Significant number of flood deaths are attributed to unnecessary risky behavior [22] and [7], like driving over the flooded path by ignoring dangers such as overlooking cautions and neglecting safety barriers [23]. In many situations, the victims are unwilling to change the route and drive through the flooded street (low water crossing) [24] and [25]. Thus, it is believed that the existing safety guidelines require major modifications based on the varying characteristics of modern cars *(static)* as well as the impact of varying hydrodynamic forces on the vehicles *(non-stationary)* attempting to cross such flooded streets. Further, the enhanced features, namely traction control and electronic stability of modern cars should also be taken into consideration to ensure the effective use of all the traction available on the low-friction flooded street.

Herein an attempt has been made to individually discuss and analyze the recommended stability zones highlighted in previous guidelines (1986-2011). Moreover, the limit functions presented in recent works (2010-2017) have also been conversed and compared with the AR&R (2011) guideline. Lastly, an effort has been made to report non-static vehicles jeopardized by floodwaters, for the very first time. Thus, the algorithms of the hydrodynamic studies for the non-stationary flooded cars into safe stability limits will be offered and compared, under the consideration of few modified parameters, which involves the rolling resistance generated at vehicle tires, drag impact at vehicle's front end and driving force caused by vehicle engine.

2. Earlier Investigations (1967-1993)

The safety recommendations offered for vehicle stability in floodwaters rely on the buoyancy depths and constant limiting velocity × depth ($v \cdot y$) functions, obtained during the empirical inquiries conducted in the late 1960s and early 1970s; and the theoretical analysis performed in the early 1990s. The main focus being the static vehicles, these recommendations are still being complied mainly because no significant research was reported between Keller and Mitsch's (1993) and Teo *et al.*'s work (2010). However, under this section, the summary of earlier investigations conducted by Bonham and Hattersley (1967), Gordon and Stone (1973) and Keller and Mitsch (1993) has been presented [26].

Table 1 summarizes the empirical and analytical approaches undertaken in the past (1967-1993), while highlighting the key findings and significant parameters.

Bonham and Hattersley (1967) obtained the line of constant friction that ranged between $\mu = 0.3$ to $\mu = 0.5$ for Ford Falcon. However, after correspondence with various test laboratories and roading experts, $\mu = 0.3$ was chosen. This value of friction coefficient was suggested satisfactory for several surface types. However, Gordon and Stone (1973) contradicted this single constant value of $\mu = 0.3$ as the range of coefficients obtained for Morris Mini Sedan were between $\mu = 0.3$ (skidding on wet surfaces) and $\mu = 1.0$ (stationary on wet surface). Further investigations by Yandell (1973) [27] and Woods *et al.*

(1960) [28] obtained the range of friction coefficients between 0.85 and 1.15 and between 0.16 to 0.48, for the stationary and skidding values, respectively. Therefore, the coefficient of μ = 0.3 suggested by Bonham and Hattersley (1967) was considered likely conservative. Bearing in mind these conflicts, Keller and Mitsch (1993) still chosen the friction coefficient of μ = 0.3 for the theoretical assessment of variety of vehicles available that time.

3. Stability Guidelines (1986-2011)

Under this section, a comprehensive explanation on the available guidelines (1986-2011) based on the upper bounds on both the hydraulic variables and the limiting product of water depth and velocity ($v \cdot y$) functions for static vehicles has been presented. Later, the limits functions have been compared with the stability zones highlighted in earlier works (1967-1993).

3.1. Department of Public Works, New South Wales (DPW, 1986)

Pertaining to stability of vehicles in floodwaters, there were very few studies available by the time this manual was published. This manual solely followed the stability limits developed from the work of Gordan and Stone (1973). On the other hand, the allowable limits highlighted for the stability of pedestrians relied on the investigations carried out by Foster and Cox (1973) [29]. The relationships presented within this manual does not indicate constant ($v \cdot y$) relationships [30] but do place upper bounds on both depth and velocity. For vehicles, the allowable limits of stability were ensured when the maximum water depth and flow velocity approaches 0.3 m and 2.0 m/s, respectively [12], whereas for pedestrians, it was recommended to be 0.8 m and 2.0 m/s, respectively as shown in Figure 1 [31].

3.2. Australian Rainfall and Runoff Guidelines (AR&R, 1987)

The criterion regarding stability of vehicles and pedestrian highlighted in the Australian Rainfall and Runoff (AR&R, 1987) indicates constant velocity-depth ($v \cdot y$) relationships. For instance, where vehicles alone were affected, a ($v \cdot y$) product of either 0.6 or 0.7 m^2s^{-1} was proposed based on vehicle type, *i.e.*, small passenger car, sport utility vehicle (SUV), etc. On the other hand, for pedestrians, the ($v \cdot y$) product of 0.4 m^2s^{-1} was recommended. The ($v \cdot y$) relationships proposed herein for the vehicles were comparatively higher than pedestrians, unlike the allowable limits as advised in DPW, 1986. The limit functions proposed in AR&R, 1987 both for vehicles and pedestrians are shown in Figure 2 [11] and [31].

3.3. Melbourne Water Land Development Manual: Flood Safety Criteria (MWLDM, 1996)

The Melbourne Water Land Development Manual (MWLDM, 1996) defines the guidelines pertaining to vehicles safety in floodwaters. These guidelines were prepared to standardise and simplify the application and computation of floodway safety requirements in the Melbourne region, Australia. The safety limits mentioned in the manual are based on the constant ($v \cdot y$) values which varies as a function of floodwater depth along the site. The recommendations proposed herein were adapted from the research results reported by Keller and Mitsch (1993). However, the allowable limits for vehicle stability highlighted in the manual are shown in Figure 3 [32] and [33].

3.4. Emergency Management Australia (EMA, 1997)

The Emergency Management Australia is the state agency which manages the disaster conditions in Australia. In the planning of emergency situations regarding floods, this organization has published several handbooks to assist other local and government organizations. The EMA, 1997 guide on four-wheel drive (4WD) vehicle operation, focused at the general guidelines which were advisable to large, four-wheel drive emergency vehicles only and were not meant for the ordinary motorists as shown in Figure 4. Concisely, the manual states that for water crossings, "*Upon entering the water, if the water level reaches to the front bumper bar or higher, accelerate until a bow wave is formed in front of the vehicle to keep the water out of the engine, keep a steady pace to maintain this bow wave at all costs.*" With that regards, a canvas sheet or tarp across the grille was recommended to prevent the water from entering the engine bay. Furthermore, it was advised to fit a snorkel extension to the engine air inlet and spray the ignition system with a dewatering fluid [34].

3.5. Emergency Management Australia (EMA, 1999)

This updated version of EMA, 1997 manual collects the best practice principles for flood plain management in Australia. It has been stressed that these principles are *guidelines* (a non-specific rule) and *not directives*. As a part of floodplain management process, these principles should not be neglected and must be considered to deal with the flood-related issues. With regards to flood hazards pertaining to vehicles, the EMA, 1999 manual highlights that "*the small, light, low motor vehicles crossing rapidly-flowing causeways can become unstable when the water depths surpass 0.3 m, whereas evacuation by larger, higher sedans is generally only possible and safe when the water depths are below 0.4 m.*" The manual further states that when the depth of still water exceeds 1.2 m, the velocity of shallow water exceeds 0.8 m/s and for various velocity-depth combinations between these limits, the wading becomes difficult by able-bodied adults. Factors like depressions, ground surface evenness, fences, potholes, etc., also need to be considered while assessing the safety of wading. Moreover, at low flow velocities and at depths in excess of 2 m, light framed buildings can still sustain damage from water pressure, debris impact and floatation [35].

3.6. Moore and Power (2002)

For the irrigation of broad-acre crops, off-stream water supply storages (ring tanks) are being commonly used in Queensland, Australia. Many of these ring tanks are sited close to main roads (within 50 m of public roads) which arouse the question of potential safety hazards in case of structure failure. To stimulate the dam break conditions for a typical ring tank, a flood-wave model was applied, output of which was then analysed to determine the safe buffer distance between the road and the ring tank with regards to vehicles safety. Based on the outcomes attained, the study proposed a safe buffer distance of 250 m to 400 m depending on the final breach width.

Concisely, the stability limits proposed by Moore and Power (2002) recommends that the buoyant force dominates stability at high depths and low flow velocities. Conversely, drag force controls stability at shallow depths and high flows. On that basis, it was instructed that the functional form of stability limits changes at the transition between sub-critical to super-critical flow conditions [36]. Based on that justification, a constant depth-velocity ($D.V$) rate was advised for the super-critical regime (drag dominates; V > 1.81), whereas a linear relation was proposed for the sub-critical regime (buoyant forces dominate; V < 1.81) [12] and [13]. Thus, the functional form of stability envelope adopted by Moore and Power (2002), states:

$$D*V \leq 0.6 \text{ for } V > 1.81 \text{ m/s (super-critical regime: drag dominates)} \quad (1)$$

$$D \leq (0.4 - 0.0376V) \text{ for } V \leq 1.81 \text{ m/s (sub-critical regime: buoyancy dominates)} \quad (2)$$

where, D is the flood depth (m), and V is the average velocity (m/s).

3.7. Floodplain Development Manual (DIPNR, 2005)

This manual is based on the provisional hydraulic hazard categories, namely high hazard and low hazard zones. It follows the velocity-depth relationships that defines vehicle stability presented within the Department of Public Works Manual (DPW, 1986) as shown in Figure 5 (a). The low and high hazard categories highlighted herein are provisional because it does not reflect the effects of other factors which could influence hazard. Therefore, when such factors are qualified and identified then the provisional hazard categories should be altered to develop *true hazard categories*.

Among *low hazard categories*, should it be necessary, truck could evacuate people and their possessions; whereas able-bodied adults would face problems in wading. Among *high hazard categories*, there is a likelihood of the risk to the personal safety, wading to safety for the able-bodied adults would be very difficult, evacuation by trucks would be very difficult and the potential for significant structural damage to buildings is possible. Further, in the transition zone, the hazard impact is dependent on the flood site conditions and the nature of the proposed development as shown in Figure 5 (b).

The above figure presents a tool for preparing an appropriate floodplain risk management plan (a strategic planning document). However, to use the provisional hydraulic hazard categories, it was essential to know the average flood depth and velocity at various places in a flood prone area. It was further recommended that as a part of floodplain risk management study, it may be appropriate for councils to prepare "hazard maps", which define areas of low and high hazard across the flood prone regions for the potential range of floods [37].

3.8. Austroads Guide to Road Design (2008)

This guide recommends that "*based on the length of floodway and flow velocity, floodwater depths ≤ 300 mm are considered passable for passenger cars*". It further mentions that if the total head which is equivalent to water depth plus the amount of kinetic energy per unit weight of fluid to raise it to a certain height (velocity head) exceeds 300 mm above the crest of a carriageway, then the carriageway should be closed for vehicles movement which in other words is also called *Time of Closure (ToC)* [38]. However, this typical adopted safe limit can be given as:

$$h = d + v^2/2g \leq 300 \text{ mm} \qquad (3)$$

where, h is the total head, d is the flood water depth, v is the flow velocity, g is the acceleration due to gravity and mm represent millimetres.

3.9. Australian Rainfall and Runoff (AR&R) - Project 10: Appropriate Safety Criteria for Vehicles (2011)

Australian Rainfall and Runoff is one of the widely used guidelines published by Engineers Australia (EA) since 1958 (*first publication*). However, these guidelines are now becoming outdated due to numerous changes in vehicle features. Herein the updated *Draft Stability Criteria* for the stability of static vehicles in floodwaters has been proposed. This draft is proposed for three vehicle classes, namely small, large and four-wheel drive (4WD) vehicles as shown in Table 2. The draft was proposed with the floating limits and the limiting depths and velocities for the given vehicle categories. Since the safety of pedestrians appears to be overlooked in many manuals except for the Public Works Department (1986) and Floodplain Development Manual (2005) [12], therefore, AR&R, 2011 guideline was combined with the stability criteria for pedestrians recommended in the published work of Cox *et al.* (2010) to ensure that the safety of the pedestrian would not be at risk once people vacant their cars in case of vehicle stability failure as shown in Figure 6 [39].

Table 3 shows the summary of guidelines in terms of limiting flow velocities and water depths proposed for vehicle stability on flooded streets.

Number of recommendations and guidelines for vehicle stability have been advised since the mid-1980s till 2011. Since then modern vehicles have undergone several timely enhancements, notably in the form of sealing capacity, vehicle's geometric nature, weight and ground clearance. As a result, it is unlikely that the limiting thresholds proposed earlier for the old-fashioned cars could be implemented directly to the modern vehicles. Thus, there is need to revise the criterion regarding stability of vehicles in floodwaters [12].

In the following section, the limiting flow velocities and water depths proposed for vehicle stability on flooded streets in different safety guidelines have been compared with the earlier investigations (1967-1993). This ensured that the stability limits proposed within these safety guidelines either complied to the safety regions highlighted in earlier works or not. Figure 7 shows the compilation of earlier works carried by Bonham and Hattersley (1967), Gordon and Stone (1973) and Keller and Mitsch (1993).

The limit functions proposed for the vehicles within DPW (1986), which were later adopted within DIPNR (2005) indicated a maximum water depth of 0.3 m and a maximum velocity of 2.0 m/s. The proposed upper bounds on both depth and velocity were below all the test results conducted by Bonham and Hattersley (1967), Gordon and Stone (1973) and Keller and Mitsch (1993) as shown in Figure 8.

On the other hand, the criterion regarding stability of vehicles highlighted in the AR&R (1987) exceeded the limits of experimental testing, *i.e.,* these values were above the test results of Bonham and Hattersley (1967) in high depths and low flow regime. Moreover, it also surpassed the limits of experimental testing performed by Gordan and Stone (1973). Though, by the time AR&R (1987) was published, the theoretical assessment by Keller and Mitsche (1993) did not take place. However, just for the sake of comparison it can be noticed that the AR&R (1987) complied to the work of Keller and Mitsche (1993) in low depths and high flow regime as shown in Figure 9.

The guidelines recommended within MWLDM (1996) were acquired from the research results reported by Keller and Mitsch (1993). However, it has been recognized that the proposed limit functions exceeded all test results in high depths and low flow velocities as shown in Figure 10.

The recommendations suggested for the vehicle stability adapted within EMA (1997) are simplistic which states that "if the water level reaches to the front bumper bar or higher, accelerate until a bow wave is formed in front of the vehicle to keep water out of the engine". Similarly, within EMA (1999), water depths below 0.3 m were recommended safe for the small passenger vehicles, whereas below 0.4 m, it was considered passable for higher sedans as shown in Figure 11.

Moore and Power (2002) for the very first time proposed the functional form of stability envelope based on the transition of flow regime. It was believed that the state of the flow matters on the behaviour of the vehicles and their stability in floodwaters. On that justification, a linear relation for sub-critical regimes, whereas a constant ($v \cdot y$) rate for super-critical regimes was assumed as shown in Figure 12.

Concerning Austroads (2008), the time of road closure was proposed if the floodwater depth exceeds 0.3 m. However, the proposed criterion might be appropriate for small vehicles, but it has been suggested to be overconservative for 4WD vehicles with higher ground clearance as shown in Figure 13.

Lastly, the AR&R (2011) guideline set an updated *Draft Stability Criteria* for the stability of static vehicles incorporated with human stability criterion presented within Cox *et al.* (2010). The limiting criteria proposed herein ensured that people safety would not be compromised once they abandon their cars in the event of vehicle failure. The stability limits proposed in the stability draft are highlighted in Figure 14.

4. Present Investigations (2010-2017)

Roadway designs and car dimensions have enhanced with time; thus, a diversity in vehicle shapes has been reported since those earlier studies. The aerodynamic shape might have improved the hydrodynamic behavior to an extent, but in contrast, modern vehicles with low ground clearance have increased the chances of instability when flooded [40]. Being concise, no significant study was reported in the domain of flooded vehicles between 1993 till 2010. Therefore, the limits concerning vehicles balance in floodwaters relies on the limiting functions highlighted in the former investigations (1967-1993). However, the description of stability criterion for modern vehicles (*static*) recommended by several authors in recent years (2010-2017) has been well explained in the published work of the authors [26].

Table 4 summarizes the empirical and analytical approaches undertaken on modern cars in recent years (2010-2017), while highlighting the key findings and significant parameters.

The AR&R (2011) guideline being the latest and most up to date report concerning safety limits for flooded vehicles, thus a detailed comparison of the proposed limits highlighted in subsequent theoretical and experimental studies (static vehicles, 2010-2017) which were not considered by the time AR&R (2011) guideline was published have been compared as shown in Figure 15 [13]. From the graph, it can be inferred that some of the limiting thresholds highlighted in the work of Xia *et al.* (2013), Oshikawa *et al.* (2011) and Shu *et al.* (2011) were below the safety zone proposed for the large four-wheel-drive (4WD) vehicles. Similarly, only two instability points were found to be underneath the stability limits proposed for the large passenger cars, corresponding to a sedan vehicle type of Toda *et al.* (2013) and Oshikawa *et al.* (2011). Overall, for majority of the static vehicles, the limiting thresholds exceeded the safety limits proposed in the AR&R (2011) guideline. Thus, the AR&R (2011) guideline remains valid and safe for the variety of cars tested in recent years ensuring that people safety would not be compromised once they abandon their flooded cars in the event of vehicle failure.

5. Future Works (2017 onwards)

Floodwater is capable to slide cars at the lowermost hydraulic variables. The direction of incoming, ground clearance, aerodynamic chassis design and vehicle weight attributes to the way floodwaters affect and control the vehicle. From the available data, it seems that all reported studies pertaining to vehicle instabilities in floodwaters are solely dedicated to static (parked) vehicles which eventually brought to the need of this research.

In former studies, the impact of hydrodynamic forces on parked vehicles (static condition) has been well explained. The frictional force for the given condition mainly emphasis on the static friction coefficient due to applied braking conditions. However, concerning non-static vehicles, several hydrodynamic parameters including friction type between the ground surface and vehicle ties changes. For instance, when a non-vehicle crosses a flat flooded roadway where the incoming flow direction remains perpendicular to direction of vehicle progress, then the frictional resistance acts in two directions, namely the rolling friction which is generated at the tires in the direction of vehicle movement due to tires rotation (F_{RO}) and frictional resistance at the tires in the opposite direction of the incoming flow (F_R). Aside from that, an additional force also called driving force (F_{DV}) is established which defies the drag generated by the flood flow. Apart from this, the impact of drag force differs for the non-stationary cars under the given circumstances as it does not only impact the frontal bonnet area of non-static vehicle but also the vehicle side end projected normal to the flow. The detailed description of the hydrodynamic forces and the mechanics of moving tires and driving force have been highlighted in the published work of the author Shah *et al.* (2019) [26]. The experimental investigations on the non-static model vehicle were performed at the Hydraulics laboratory located at Universiti Teknologi PETRONAS, Malaysia. A hatch back Malaysian made Perodua Viva, that portrays the typical size of passenger vehicles was modelled (1:10), ensuring the similarity laws. A set of measurements involved the water depth on the platform (y) and the velocity of the incoming flow (v) for each experiment. Further, the driving force of the vehicle was assessed by noticing the time taken by the vehicle to reach a known distance as shown in Figure 16.

5.1 Formula Validation

The way how instability failure occurs for the static vehicles has been well recognized in the former articles. Herein the focus would be more on the instability modes, a non-static car could face while attempting to pass a flooded street (flat). With that regards, the vertical pushing force which could cause floating failure and the horizontal pushing force responsible to cause sliding mechanism, have been theoretically assessed. Since the study was performed under subcritical flow conditions, therefore concerning vertical pushing force, only the impact of buoyancy force was taken into account. In contrast, the impact of horizontal pushing force, namely drag force at vehicle’s side end, frictional forces (both at F_R and F_{RO}) and the driving force (F_{DV}) of the vehicle were taken into consideration for the assessment of sliding failure mechanism.

Pertaining to moving vehicles, the criterion for floating instability remains same as for the static cars specifically for subcritical flows. This criterion could differ for other flow conditions, namely super-critical and critical flows which would lead to the inclusion of lift force for determining the vertical pushing force. Concerning sliding failure, it has been identified that the friction and the driving forces oppose the drag caused by flood flow. Therefore, if the drag exceeds the frictional and driving forces, then there is a possibility that a moving car progressing slowly on a flooded roadway may slide. Based on the given conditions, an incipient velocity formula that would lead to the sliding instability failure for a non-static car was proposed. However, to determine the accuracy of proposed formulation, the incipient velocity required to cause sliding instability of a partially submerged flooded vehicle were experimentally and theoretically validated. Figure 17 displays the linear regression between the incipient velocities attained through laboratory investigations and the calculations obtained from the proposed formulation. Overall, a good agreement between the two was observed with the correlation coefficient of $R^2 = 0.85$ [26].

5.2 Stability Limits

The main findings pertaining non-static vehicle in floodwaters have highlighted that the buoyancy force governed vehicle weight at depths ≥ 0.0457 m, whereas below this point, the dominancy of drag force over frictional resistance and driving force caused sliding failure. The drag impact at vehicle's front end was noticed to be nominal mainly due to low velocity and the availability of smaller submerged area. The values of friction coefficient for the *non-stationary vehicle* were experimentally determined for the very first time. However, the value of coefficients for the frictional resistance (μ) and rolling resistance (μ_{RO}) were found to be 0.52 and 0.092, respectively. It was further observed that the relation between the empirical investigations and the theoretical assessment complied very well to each other. The percentage of error between the two was noticed to be below 2%. Below buoyancy depth, *i.e.*, < 0.0457 m, the possibility of a vehicle to slide relied on the product of velocity × depth function. For instance, a range of velocity-depth relationship was witnessed where the vehicle was found to be sliding. However, the $v{\cdot}y_{fit}$ to cause sliding failure obtained from the experimental investigation and later validated through theoretical assessment was found to be 0.70 m²/s. Below this limiting threshold, the vehicle was found stable. Thus, for the equation of stability, it has been recommended that a small passenger car (weighing ≤ 800 kg) slowly progressing on a flat flooded roadway (subcritical flow) remains stable if the $v{\cdot}y$ function is less than 0.70 m²/s as shown in Figure 18.

5.3 Comparison of Instability Thresholds

For the sake of comparison, herein an attempt has been made to analyze the limiting thresholds attained for the non-static Perodua Viva with the instability points highlighted in earlier and recent works.

5.3.1 Comparison with earlier works (1967-1993)

Under this section, the limiting thresholds attained for the old-fashioned static cars in earlier works, namely the experimental investigations performed by Bonham and Hattersley (1967) and Gordon and Stone (1973); and the theoretical analysis assessed on the variety of vehicles by Keller and Mitsch (1993) have been compared with the experimental investigations conducted by as Shah *et al.* (2019) as shown in Figure 19.

The results attained for the non-static vehicle were below the test results of Bonham and Hattersley (1967). However, it surpassed all the test results for the Morris Mini with the rear wheel locked condition. Moreover, the buoyancy depth proposed herein was below the buoyancy depth proposed for the Morris Mini with the front wheel locked condition. However, it exceeded the limiting velocity × depth ($v \cdot y$) functions derived for the given conditions. It can further be noticed that ($v \cdot y$) functions proposed herein exceeded the limiting thresholds for the variety of cars theoretically assessed by Keller and Mitsche (1993) at high depths and low velocities, whereas it agreed well to given instability points at low depths and high flow regime.

It can further be inferred, that the floating limit proposed herein for the Perodua Viva was below the buoyancy depths recommended for Ford Falcon and Morris Mini (front wheels locked condition). This difference is mainly due to vehicle weight. In those olden days, cars were built on sturdy steel frames and had nice, thick sheet metal bodies. However, in the present era, vehicles are made up of carbon fiber and when combined with a polymer, can be molded into the shape that is stronger and lighter than steel and aluminum parts excessively used in the earlier days. On the other hand, one of the causes why contemporary cars can quickly swept away even at low flood depths is also attributed to vehicle’s sealing capacity. Proper sealing capacity ensures better temperature control (air conditioner) and helps to diminish the exposure of outside contaminants. However, this does not allow floodwater to seep inside the car. Thus, it ensures bigger submerged fractions to the vertical pushing force during flooding conditions. Therefore, even at shallow flood depths, a light weight passenger car could compromise stability as the vehicle base contacts floodwater [41]. It is to be emphasized that the study outcomes attained for the non-static car in this article are valid for the subcritical flows only, thus it is believed that the buoyancy depth could slightly differ for critical and supercritical flow conditions due to the inclusion of lift force.

5.3.2 Comparison with recent works (2010-2017)

The limit functions proposed for the vehicles in recent years (2010-2017) that involves a variety of modern static cars have been compared with the non-static Perodua Viva as shown in Figure 20.

Prior to compare the limiting thresholds, it is important to emphasize that the AR&R (2011) set an updated *Draft Stability Criteria* for the stability of static vehicles incorporated with human stability criterion presented within

Cox *et al.* (2010), *i.e.*, the ($v \cdot y$) value less than 0.6 m^2/s. However, the limiting thresholds criterion proposed for the non-static vehicle compromised the given safety limit because the minimum ($v \cdot y$) value to cause sliding failure obtained from the experimental investigation and later validated through theoretical assessment was found to be > 0.60 m^2/s. Thus, it can be concluded that in case of non-static vehicles attempting to cross a flat flooded roadway, the passengers are recommended not to abandon their vehicles because if the incoming flow is sufficient to make the vehicle slide then it would probably be very difficult for the people to wade. It can be noticed that the instability points proposed for non-static car were below the velocity × depth ($v \cdot y$) functions presented for variety of cars tested in recent years (2010-2017). However, the velocity × depth ($v \cdot y$) functions presented for the non-static vehicle exceeded the stable zones proposed for all vehicles type in the AR&R (2011) guideline. Thus, the AR&R (2011) guideline still remains valid and safe for all car types.

6. Conclusions

In this article, the algorithms of the hydrodynamic studies for the non-static vehicles into safe stability limits were presented to further enhance the existing hazard criteria for the reliable application of safety guidelines to urban flood scale. With that regards, a comparison of limiting thresholds attained for the modern (non-static) vehicle with the old-fashioned (static) and modern (static) vehicles was performed. Though, in author’s view, it is not justifiable to compare the limiting thresholds of a non-static car with static ones. However, there has not been performed any study on the non-static and this was the only study of its kind, thus in future, a better comparison can only be made once the studies on the non-static vehicles are available. In summary, at this stage, it is believed that AR&R (2011) guideline still remain valid and safe for the old-fashioned static vehicles, modern static vehicles and modern non-static passenger cars.

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